12.

EXPERIMENTS AND OBSERVATIONS

ON THE

UNEQUAL REFRANGIBILITY OF LIGHT:

FROM THE

TRANSACTIONS

OF THE

ROYAL SOCIETY OF EDINBURGH.

EXPERIMENTS *and* OBSERVATIONS *on the* UNEQUAL REFRANGIBILITY *of* LIGHT. *By* ROBERT BLAIR, M. D.

[*Read Jan.* 3. *and April* 4. 1791.]

BY the diſcovery of the different refrangibility of light, Sir ISAAC NEWTON laid open the true cauſe of the principal imperfection of refracting teleſcopes; and having inferred from the experiments which he made, that the refraction of the different rays compoſing the priſmatic ſpectrum, was always in a given ratio to the refraction of the mean refrangible ray, this great philoſopher was led to conclude, that the imperfection which he had diſcovered in dioptrical inſtruments was without remedy.

IF Sir ISAAC NEWTON had been queſtioned concerning the poſſibility of refracting light, without any divergency of the heterogeneal rays, his reply without doubt would have been, that all his experiments, whether by ſingle refractions or by oppoſite refractions, tended to eſtabliſh the contrary concluſion. But that he would have aſſerted nothing beyond this, may ſafely be inferred from his own memorable words; “Although “the arguing from experiments and obſervations by induction “be no demonſtration of general concluſions, yet it is the beſt

" way of arguing which the nature of things admits of, and
" may be looked upon as ſo much the ſtronger by how much
" the induction is more general; and if no exception occur
" from phenomena, the concluſion may be pronounced gene-
" rally; but if at any time afterwards any exception ſhall
" occur from experiments, it may then begin to be pronounced
" with ſuch exceptions as occur."

THIS is the general doctrine which he lays down as applicable in all experimental enquiries; and ſo far was he from conſidering the particular caſe above mentioned as an exception to this general rule, that from ſome expreſſions he makes uſe of, it evidently appears, that he was not without ſuſpicion, of what has ſince been diſcovered to be the truth.

IN his ſixth letter to Mr OLDENBURGH, dated from Cambridge in the year 1662, he expreſſeth himſelf in the following words: " Mr HOOK thinks himſelf concerned to reprehend
" me for laying aſide the thoughts of improving optics by re-
" fraction. What I ſaid there was in reſpect of teleſcopes of
" the ordinary conſtruction, ſignifying that their improvement
" is not to be expected from the well figuring of glaſſes, as op-
" ticians have imagined. But I deſpaired not of their im-
" provement by other conſtructions, which made me cautious
" to inſert nothing that might intimate the contrary. For al-
" though ſucceſſive refractions which are all made the ſame
" way, do neceſſarily more and more augment the errors of
" the firſt refraction, yet it ſeemed not impoſſible for contrary
" refractions ſo to correct each others unequalities, as to make
" their difference regular; and if that could be conveniently
" effected, there would be no farther difficulty. Now to this
" end I examined what may be done, not only by glaſſes alone,
" but more eſpecially by a complication of diverſe ſucceſſive
" mediums; as by two or more glaſſes or cryſtals, with water,
" or ſome other fluid, between them; all which together may
" perform the office of one glaſs, eſpecially of the object glaſs,

" on whoſe conſtruction the perfection of the inſtrument " chiefly depends. But what the reſults in theory or by trials " have been, I may poſſibly find a more proper occaſion to de- " clare."

In the year 1757, the late Mr John Dollond, in conſequence of ſome ſtrictures on Sir Isaac Newton from abroad, repeated the noted experiment of refracting a ray of light through priſms of glaſs and water, placed with their refracting angles in oppoſite directions, and ſo proportioned to each other, that the ray, after theſe oppoſite refractions, emerged parallel to the incident ray. According to the Newtonian doctrine, there ought here to have been no divergency of the heterogeneal rays, and no colour produced by theſe equal and oppoſite refractions.

But this was not the reſult of the experiment. The ray was coloured very ſenſibly; and the author of the experiment finding that he could, by theſe oppoſite refractions, produce colour, notwithſtanding the paralleliſm of the incident and emergent light, with reaſon concluded that he might, by properly proportioning the refracting angles of his priſms, effect an inclination of the refracted to the incident light, without any colour or divergency. The event turned out as he expected.

Pushing his experiments farther, he diſcovered, ſome time afterwards, that a colourleſs refraction might be produced by a combination of different kinds of glaſs, as well as by a combination of glaſs and water, which ſeemed to remove completely the great obſtacle to the perfection of the refracting teleſcope, diſcovered by Sir Isaac Newton.

As it was found ſoon afterwards, that the other principal imperfection which limits the performance of teleſcopes, namely, the aberration ariſing from the ſpherical figures of lenſes, might be corrected by properly proportioning to each other the ſphericities of the convex and concave lenſes, of which the compound object glaſs is compoſed; it was expected by men of ſcience, that an increaſe of the aperture and power of the inſtrument,

ſtrument, would be the neceſſary conſequence of ſuch important ſteps, towards the perfection of its theory. Theſe expectations have not hitherto been fully anſwered.

If the theory of the achromatic teleſcope is ſo complete as it has been repreſented, may it not reaſonably be demanded, whence it proceeds, that Hugenius and others could execute teleſcopes with ſingle object glaſſes eight inches and upwards in diameter, while a compound object glaſs of half theſe dimenſions, is hardly to be met with? or how it can ariſe from any defect in the execution, that reflectors can be made ſo much ſhorter than achromatic refractors of equal apertures, when it is well known that the latter are much leſs affected by any imperfections in the execution of the lenſes compoſing the object glaſs, than reflectors are by equal defects in the figure of the great ſpeculum?

The general anſwer made by artiſts to enquiries of this kind, is, that the fault lies in the imperfection of glaſs, and particularly in that kind of glaſs of which the concave lens of the compound object glaſs is formed, called flint-glaſs.

It was in order to ſatisfy myſelf concerning the reality of this difficulty, and to attempt to remove it, that I engaged in the following courſe of experiments. The reſult of this inveſtigation I now do myſelf the honour of ſubmitting to the Royal Society.

The imperfections of glaſs for optical purpoſes ariſe partly from its want of perfect tranſparency, and from being more or leſs affected with a tinge of ſome particular colour, but principally from irregularities which are frequently found in its refractive denſity. This laſt imperfection is ſo conſtant an attendant upon flint-glaſs, and every other kind of glaſs which poſſeſſes the diſperſive quality in a conſiderable degree, that it has been ſuſpected, not without appearance of reaſon, to ariſe neceſſarily from that ingredient in its compoſition on which this quality depends. It is certain that great labour and expence have been beſtowed on this object without the deſired effect.

CONSIDERING therefore that it is not impoſſible to introduce a fluid medium to ſupply the place of one of the lenſes, in the compound achromatic object glaſs, I was deſirous of ſearching whether nature afforded fluids poſſeſſed of the requiſite qualities.

IT appears from the paſſage already quoted, that Sir ISAAC NEWTON not only ſuſpected that optical inſtruments might admit of improvement by a combination of ſolid and fluid mediums, but had actually made experiments on the ſubject, and conſidered this as the moſt likely means of carrying theſe inſtruments to their greateſt perfection.

Dr DAVID GREGORY, Savilian profeſſor of aſtronomy at Oxford, entertained ſimilar ideas on this ſubject, as appears from his treatiſe, entitled, "Catoptricæ et Dioptricæ Sphæricæ "Elementa." In this work, which was publiſhed at Edinburgh in the year 1713, he treats of optical inſtruments, both by refraction and reflection; and, after ſhewing the advantages of the latter in theory, concludes his treatiſe with the following words: "Quod ſi ob difficultates phyſicas, in ſpeculis idoneis "torno elaborandis et poliendis, etiamnum lentibus uti oporteat, fortaſſis media diverſæ denſitatis ad lentem objectivam "componendam adhibere utile foret, ut a natura factum ob"ſervemus in oculi fabrica, ubi chriſtallinus humor (fere ejuſ"dem cum vitro virtutis ad radios lucis refringendos) aqueo et "vitreo (aquæ, quoad refractionem, haud abſimilibus) conjun"gitur, ad imaginem quam diſtinctè fieri potuit, a natura ni"hil fruſtra molienti, in oculi fundo depingendam: ſed et "alii ſunt in animalis oculo, prædicti artificii uſus, qui non "ſunt hujus loci."

THIS coincidence of opinion of theſe great opticians reſpecting the ultimate perfection attainable by the teleſcope, deſerves to be remarked. Various attempts of this kind have been made by later philoſophers and artiſts. Indeed, the ſtructure of the eye, compoſed of ſolids and fluids variouſly combined, ſeems to preſent ſo obvious and inſtructive a pattern for imitation, that it is no wonder if the expectations entertained of the productions of art, roſe in proportion as they could be made to approach the conſtruction of this exquiſite model of Divine workmanſhip.

Mr Dollond's firſt experiments went no farther than to prove to him, that glaſs diſperſes the heterogeneal rays of light more than water, when the refraction of the mean refrangible ray is equal in both mediums. With theſe ſcanty data, this able artiſt zealouſly went to work to conſtruct teleſcopes on this new diſcovered principle. But on this occaſion his attempts were not attended with any degree of ſucceſs. This need not much be wondered at. Beſides the difficulty he mentions, ariſing from the ſpherical aberration, (which, by the by, if he had conſidered the matter more attentively, he would have ſeen to be eaſily ſurmountable) he would find between plate-glaſs and water, but an inconſiderable difference of diſperſive power; and if he made uſe of flint-glaſs he would have all thoſe difficulties to ſtruggle with, which his ſucceſſors have not been able to remove, though fully apprized of their cauſe.

This want of ſucceſs in his firſt trials with fluids, and the diſcovery he ſoon after made of a difference in the diſperſive power of different kinds of glaſs, which he was more ſucceſsful in applying to the improvement of teleſcopes, ſeems to have put an end to all thoughts of the uſe of fluids, nor has any thing of that kind been ſince attempted, as far as I have been able to learn, ſome unſucceſsful trials excepted, to conſtruct thoſe ſmall perſpectives called opera glaſſes, on a plan ſimilar to that of Mr Dollond, by including ſpirit of wine between two concave meniſcuſes of flint-glaſs, the fluid ſupplying the place of crown-glaſs, and the advantage propoſed being a ſaving of the light loſt by reflection.

THE experiments of Mr DOLLOND proved, that the diſperſive power of water is leſs than that of the glaſs with which he made his experiments; and it ſeems wonderful that this ſhould have been almoſt the only attempt made to inveſtigate this quality in fluid mediums. We find many tables aſcertaining the mean refractive denſity of fluids, from experiments made both before the diſcovery of DOLLOND and ſince. But though ſome of the fluids examined were poſſeſſed of the diſperſive quality in a remarkable degree, this is paſſed over unobſerved, and it would ſeem unſuſpected, if we except the very ingenious conjecture of Mr MICHEL; to whom it occurred, that the apparent difference in the experiment above mentioned, made by Sir ISAAC NEWTON, from the ſame experiment repeated by Mr DOLLOND, might ariſe from the former uſing, inſtead of pure water, a ſolution of Saccharum Saturni, which he mentions his having ſometimes made uſe of to increaſe the refraction. Mr MICHEL ſuſpected that lead, even in this form, might increaſe the diſſipative refraction, as it does in the compoſition of glaſs. The reſult of his experiments on this ſubject may be ſeen in the additions to Dr PRIESTLEY's Optics, at the end of the ſecond volume.

Of the methods employed for inveſtigating the optical qualities of different mediums.

IN aſcertaining the mean refractive and diſperſive qualities of fluids, I made uſe of two kinds of apparatus. Where the properties of the fluids were entirely unknown, priſms were employed to come to a groſs knowledge of their properties, and thoſe fluids which promiſed to be of uſe in the practical part of optics, were more critically examined by means of lenſes, where the effect, from being magnified, becomes more conſpicuous.

The priſmatic apparatus conſiſts of a ſmall priſm of braſs, whoſe three angles are equal. Through this priſm, and parallel with one of its ſides, are bored two holes at a ſmall diſtance from each other, equal in ſize to the pupil of the eye. The ſides of the priſm are ground flat, and there are two bits of glaſs with parallel ſides, of the ſame dimenſions as the ſides of the priſm. There are alſo priſms of the ſame ſize, and with the ſame angles of different kinds of glaſs, and ſome crown-glaſs priſms, with ſmaller angles, which, by being applied to the large priſm, or to each other, vary the refracting angle at pleaſure.

When it is propoſed to try the properties of any fluid, one of the ſmall plates of glaſs is applied over the holes on the ſide of the braſs priſm. A few drops of the fluid are then dropped into the hole; and when it is full, the other plate is laid over the holes upon the oppoſite ſide, and the whole is ſecured by tying a bit of pack-thread round the ends. One of the glaſs priſms is now to be applied to the braſs priſm, contiguous with one of the parallel plates, the refracting angles of the two priſms being placed in oppoſite directions, ſo as to form a ſmall parallelepiped.

Nothing farther is neceſſary than to apply the eye to the hole which contains the fluid, in ſuch a way as to obſerve through it any bright well defined object. The bars of the window anſwer the purpoſe very well in the day-time, and the moon, or a candle in the night. The intention of the two holes is for the ſake of greater expedition. The properties of two fluids may thus be examined and compared at the ſame time.

As the priſmatic portion of fluid and the glaſs priſm have equal refracting angles, and refract in oppoſition to each other, it will eaſily be underſtood, that if the object ſeen through the two priſms coincides with the ſame object ſeen directly, the mean refractive denſity of both mediums will be the ſame. When this is the caſe, if the object ſeen through theſe priſms appears free from priſmatic colour, the diſperſive power of the fluid medium is alſo the ſame with the diſperſive power of the glaſs priſm. But otherwiſe they will be different.

Those mediums, it is to be obſerved, are ſaid to have the ſame mean refractive denſity, which, under equal obliquities of incidence, equally refract the mean refrangible rays, and two mediums are ſaid to have the ſame diſperſive power, which produce an equal inclination of rays of the ſame colour, to the mean refrangible ray, when the whole refraction of the mean refrangible ray is equal in both.

When an object, ſeen through the equal wedges of glaſs and fluid, appears coloured, one of the ſmaller glaſs wedges is to be applied and ſhifted till the object appears colourleſs. It is eaſy to diſtinguiſh, by the order in which the priſmatic colour lies, whether the ſmall priſm is to be applied in ſuch a way as to increaſe the diſperſion of the rays occaſioned by the fluid, ſo as to enable it to counterbalance that of the glaſs; or whether the refracting angle of the glaſs priſm requires to be enlarged, to enable it to counteract the diſperſion occaſioned by the fluid.

By proceeding in this way to ſhift the angles of the priſms, till, firſt, the direct and refracted images of an object coincide, without regarding the colour; and, next, till the refracted image appears colourleſs, without regarding the coincidence; the ratio of the mean refractive and diſperſive powers of that kind of fluid, and that kind of glaſs, with which the experiments are made, will be obtained, from the angles of the priſms being given in both caſes.

In order to aſcertain the abſolute refractive denſity of glaſs, or any other medium, that is to ſay, the general ratio of the ſines of the angles of incidence to the ſines of the angles of refraction of the mean refrangible ray, which obtains in that medium, I took a direct method, ſimilar in principle to that employed by Sir ISAAC NEWTON, and deſcribed by him in the ſeventh propoſition of the firſt book of his Optics, and likewiſe in his Optical Lectures, p. 54. ; but which I may venture to ſay will be found much eaſier, and perfectly accurate.

INSTEAD of cauſing the rays to paſs through the ſights of a large and accurate quadrant, at the diſtance of ten or twelve feet, as directed by Sir ISAAC NEWTON, I employed a HADLEY's quadrant, in the following manner:

FIG. I.—I repreſents the index-glaſs and H the horizon-glaſs of a HADLEY's quadrant. S I repreſents a ſolar ray, incident on the index-glaſs, thence reflected to the horizon-glaſs H, and from it to the eye at E. The line s g repreſents another ſolar ray, incident on the priſm P, and through it refracted to the eye at E. When the priſm is turned ſlowly round its axis, till the ſpectrum G appears at its greateſt height, this is its proper poſition. The angle formed by the direct and refracted ray is then the leaſt poſſible, and the angles of incidence and emergence are equal. Let the priſm be ſecured in this poſition. A ſlight inſpection of the figure will ſhew, that when the reflected and refracted images of the ſun are made to coincide, the angle marked by the index of the quadrant, is the ſame which the incident ray s g forms with the refracted ray P E produced. For S Z H is the angular diſtance of the ſun and his doubly reflected image, marked by the index; and the angle s g G, which the ray incident on the priſm forms with the refracted ray produced, is equal to it; s g and S I being parallel, and P Z and H Z being coincident.

THE manner in which the ratio of the ſines of the angles of incidence and refraction may be computed from the above angle, and the refracting angle of the priſm being given, is fully explained in the celebrated works which have juſt been quoted.

It may be proper here to remark, that as it is the ratio of refraction of the mean refrangible ray which is wanted, the centre of the reflected image of the ſun ought to be made to coincide with the centre of the coloured ſpectrum, as repreſented in the figure; and if, inſtead of this, the coincidence is formed with the moſt or leaſt refrangible ray, or any of the intermediate rays, it will be the ratio of refraction of theſe rays, and not of the mean refrangible ray, which will be found from the obſervation. Hence this method might be practiſed for determining the diſperſive power, as well as the mean refractive denſity of any tranſparent ſubſtance, whether ſolid or fluid; but I have preferred a combination of priſms or lenſes, becauſe it is the relative ratios, more than the abſolute ratios, which are moſt immediately wanted.

Experiments on the diſperſive powers of fluids.

I examined, by the priſmatic apparatus which has been deſcribed, the optical properties of a great variety of fluid mediums. It will ſuffice to mention the moſt remarkable of theſe. Many ſolutions of metals and ſemi-metals, in different forms, were ſubjected to trial, and theſe were always found to be more diſperſive than crown-glaſs. The ſolution of ſome ſalts in water, as for inſtance of crude ſal ammoniacum, greatly increaſes its diſperſive power. The marine acid diſperſes very conſiderably, and this quality increaſes with its ſtrength. Hence I found the moſt diſperſive fluids to be thoſe in which the marine acid and the metals are combined. The chemical preparation called *cauſticum antimoniale* or *butyrum antimonii*, in its moſt concentrated ſtate, when it has juſt attracted ſufficient humidity to render it fluid, poſſeſſes the quality of diſperſing the rays in ſuch an aſtoniſhing degree, that three wedges of crown-glaſs are neceſſary to remove the colour produced by one wedge of this ſubſtance, of an equal refracting angle, oppoſed to them. The great quantity of the ſemi-metal retained in ſolution, and the highly concentrated ſtate of the marine acid, ſeem to be the cauſe of this ſcarce credible effect.

Corrosive ſublimate mercury, added to a ſolution of crude ſal ammoniacum in water, poſſeſſes the next place to the butter of antimony among the diſperſive fluids which I examined. It may be made of ſuch a degree of ſtrength, as to require a wedge of crown-glaſs, of double the refracting angle, to remove the colour which a priſm of it produces. The mercury and marine acid contained in this ſolution, are manifeſtly the cauſe of its diſperſive power. For neither the water nor the volatile alkali, which are its other component parts, will be found capable, if tried ſeparately, of contributing towards this effect.

The eſſential oils were found to hold the next rank to metallic ſolutions, among fluids which poſſeſs the diſperſive quality. The moſt diſperſive I found to be thoſe obtained from bituminous minerals, ſuch as the native petrolea, pit-coal and amber. When the refraction is without colour, the proportion of the refracting angle of a priſm of theſe, to the refracting angle of a priſm of crown-glaſs acting in oppoſition, is about two to three. The diſperſive power of the eſſential oil of ſaſſafras, is not much inferior to theſe. The eſſential oil of lemons, when genuine, requires the refracting angles of the priſms neceſſary to produce a colourleſs refraction, to be as three to four. In oil of turpentine, this proportion is as ſeven to ſix; and the eſſential oil of roſemary is ſtill leſs diſperſive.

Some expreſſed oils which were examined, were found not to differ ſenſibly in diſperſive power from crown-glaſs, which was alſo the caſe with rectified ſpirits, and with nitrous and vitriolic æther.

A VARIETY of other fluids were examined in the ſame way; but not having yet collected them into a table, I have only mentioned, in general terms, the moſt remarkable.

HAVING been thus ſucceſsful beyond my hopes, in diſcovering fluids capable of removing the great imperfection of teleſcopes, ariſing from the different refrangibility of light, the next object was, to ſelect from this variety thoſe which ſeemed beſt adapted to optical purpoſes.

THERE can be no doubt that thoſe mediums which moſt diſperſe the rays, are, *cæteris paribus*, to be preferred. It will alſo be found, when the method of correcting thoſe errors, which ariſe from the ſpherical figures of lenſes, comes to be conſidered, that there is apparently an advantage in uſing a diſperſive medium, whoſe mean refractive denſity exceeds the mean refractive denſity of crown-glaſs.

As the antimonial cauſtic poſſeſſes both theſe advantages, in a degree far beyond what was to be expected in any fluid, I included ſome of it between two double convex lenſes of crown-glaſs, whoſe radii of convexity were as two to one. The leaſt convex ſides of theſe were turned towards each other, and they were kept at a proper diſtance by means of a glaſs-ring. The cavity was then filled with the ſtrongeſt butter of antimony. Here it is evident that there is a concave lens of the diſperſive fluid, acting in oppoſition to the two convex lenſes of crown-glaſs, and that the proportion of the radii of theſe is the ſame which was found by the priſms to correct the colour, namely, three wedges of crown-glaſs, to one of the butter of antimony.

THIS compound object-glaſs being put into a tube, an eye-glaſs was applied, and, according to expectation, the colour was found to be removed. But I was ſurpriſed to find, on directing the inſtrument to a planet, and uſing a deep eye-glaſs, that this fluid, in its highly concentrated ſtate, was ſubject, like flint-glaſs, to great irregularities in its denſity, diſcoverable by ſtreams of light, like comet's tails, iſſuing in different directions from the diſc of Venus, which was the planet obſerved. By ſhaking the object-glaſs, theſe might be, in a great meaſure, removed, but ſoon returned; and after ſtanding all night, broad veins, in different parts of the included fluid, were perceptible to the naked eye.

It was neceſſary on this account to reject very denſe fluids. The antimonial preparation I found might be reduced to a ſufficient degree of fluidity, by mixing it with ſpirit of wine or vitriolic æther, into which a ſmall quantity of the marine acid had been previouſly dropped. This prevents any precipitation of the ſemi-metal in the form of a calx. In this diluted form, either this preparation, or the ſolution of corroſive ſublimate mercury alone, in ſpirit of wine, or in water, with the addition of crude ſal ammoniacum, may be employed for producing refraction without colour, and without being ſubject to that irregularity of denſity to which flint-glaſs, and very denſe diſperſive fluids, are ſubject.

But as ſolutions of ſaline ſubſtances in this diluted ſtate do not differ materially in diſperſive power from the eſſential oils, theſe two kinds of fluids may be uſed indifferently.

There is, however, a particular caſe, in which water or vitriolic æther, impregnated with antimony or mercury, will have the advantage, from being leſs denſe than eſſential oils; and that is, where it is required to produce a ſingle refraction, in which there ſhall be no difference of refrangibility of heterogeneal light. As this expreſſion may ſound ſtrange in the ears of opticians, I ſhall, before proceeding farther in the application of the experiments which have been recited, explain what is meant by it.

Caſes of refraction in which the violet rays are leaſt refrangible, and the red rays moſt refrangible; or in which all the rays are equally refrangible; or in which the red rays are refracted from the perpendicular, and the violet rays towards the perpendicular, while the mean refrangible rays ſuffer no refraction.

IT has been mentioned, that when priſms of crown-glaſs and oil of turpentine refract in oppoſition, the tranſmitted light is colourleſs, when the proportion of the refracting angles of theſe priſms is as ſeven to ſix. Hence, if oil of turpentine be included between two double convex lenſes, the radii of whoſe convexities are as ſix to one, and the deep ſides of theſe be placed inwards, ſo as to be in contact with the fluid; in the refraction through this compound lens, the aberration from the difference of refrangibility will be removed. I can prove the truth of what I write, by a compound object glaſs of this kind, which I have had in my poſſeſſion above four years. It is twenty inches in focal length, and its performance as a teleſcope, with one inch and a half of aperture, is not contemptible. Now, it has long ago been aſcertained, that the mean refractive denſity of oil of turpentine is leſs than that of glaſs; and thence I affirm, that when light paſſes from crown-glaſs into oil of turpentine, a conſiderable refraction of the whole pencil from the perpendicular takes place, and the violet rays are, in this caſe, the leaſt refrangible, and the red rays the moſt refrangible.

THIS is manifeſt from the facts which have juſt been ſtated. In the object-glaſs above mentioned, there are four refractions, all of which are made in the ſame direction; namely, two refractions at the two external ſurfaces of the lenſes, which are in contact with air, and two at the internal ſurfaces, which are in contact with oil of turpentine.

In the refractions which take place in the confine of glaſs and air, it has been put beyond all doubt, by Sir Isaac Newton's experiments, that the red rays are leaſt refracted, and the violet rays moſt refracted; and it is equally clear, from what has juſt been mentioned to be the reſult of trials with priſms, and from the correction of colour in the above mentioned object-glaſs, that when light paſſes obliquely out of crown-glaſs into oil of turpentine, it is refracted from the perpendicular, and the red rays are moſt refracted, and the violet rays leaſt refracted. If this were otherwiſe, the heterogeneal rays, which are made to diverge in two refractions, which take place in the confine of glaſs and air, could never have this divergency removed by the refractions made in the confine of glaſs and the fluid. It is manifeſt, that if, in theſe laſt mentioned refractions, the ſeparation of the heterogeneal rays were in the ſame order as in the refraction from air into glaſs, the colour and divergency of the rays, inſtead of being removed by them, would be increaſed.

I shall not enter upon the application of this fact to the beſt received theories of refraction; but it may be worth while to remark the great importance of minute accuracy in obſerving the reſults of experiments. Dr Hook attempted to make object-glaſſes of teleſcopes, by interpoſing a fluid between a plano-convex lens, and a piece of glaſs, both ſides of which were plane and parallel. The convex ſide of the lens was turned inwards; and the author ſeems to have had no other view in this ſcheme, but to obviate the difficulty which was found in giving a good figure to lenſes ground to very long radii. The refraction being thus reduced to that which takes place in the confine of glaſs and the fluid employed, may be diminiſhed in any proportion, and conſequently the focal length of the object-glaſs lengthened at pleaſure. One of the fluids which he appears to have made uſe of, was oil of turpentine. The difference between the phenomena attending an object-glaſs of this conſtruction and a ſimple lens, if they had been attentively obſerved, would have led Dr Hook to the truth; and a man of his zeal and invention would not have failed to apply the diſcovery to the improvement of optics, not to mention the triumph it would have afforded the opponent and rival of Newton, to have aſſerted, and had it in his power to make good his aſſertion, that in ſome caſes the violet rays are the leaſt refrangible, and the red rays the moſt refrangible.

Even Mr Dollond could not conceive that the priſmatic colour could be corrected by refractions which are all made the ſame way; and ſtill leſs would he have admitted that ſingle refractions may take place without divergency or colour *. As this continues to be the opinion of the beſt informed opticians of the preſent day, it will be neceſſary to enter into a more explicit inveſtigation of the ſubject.

Fig. 2. Let A B C repreſent a glaſs priſm, and B C D a priſm of water in contact with it; and let the angles of theſe priſms be ſo proportioned to each other, that a ray of light S I, which enters the glaſs priſm perpendicularly, ſhall, after being refracted from the perpendicular at the point G, in paſſing out of the glaſs into the water, emerge at K, perpendicular to the ſide C D of the water priſm, which is ſuppoſed to be confined by parallel plates of glaſs. As the ray both enters and emerges from the refracting mediums perpendicularly, it will ſuffer no refraction, excepting when it paſſes from the glaſs into the water, where its incidence is oblique. Here it will be refracted from the perpendicular, and will emerge coloured, the violet rays being moſt refracted, and the red rays leaſt refracted.

Let the water be now impregnated with antimony or mercury, to increaſe its diſperſive power. As this will alſo increaſe its mean refractive denſity, and occaſion a diminution of the refraction

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* Philoſophical Tranſactions of London, vol. l. page 740.

refraction in paſſing into it from the glaſs, conceive the angle BCD to be diminiſhed as the refraction diminiſhes, ſo that the refracted ray G K ſhall ſtill emerge perpendicular to D C. When the angles of the glaſs priſm and priſm of diſperſive fluid bear to each other a certain proportion, the ray will be found to emerge colourleſs; and when this happens, it is evident that all the rays are equally refracted at the point G, in paſſing out of the glaſs into the fluid. For they ſuffer no other refraction whatever.

THIS is a neceſſary conſequence of the glaſs and fluid differing in their mean refractive denſity, and of the rarer medium poſſeſſing the requiſite degree of diſperſive power.

THIS caſe of a ſingle refraction taking place, without any difference of refrangibility of the rays, may be illuſtrated by Sir ISAAC NEWTON's explication of refraction, by means of attraction, in the following manner. He ſuppoſes refraction to ariſe from an attracting force acting on light, in lines perpendicular to the ſurface of the medium; and the cauſe of one kind of rays being more refracted than another, to ariſe from their being more attracted.

WHEN the medium is ſurrounded by a vacuum, the refraction will be proportioned to the whole attracting force of that medium. But when light paſſes from one refracting medium into another, it will only be attracted by the difference between their attracting forces, as they act in oppoſition to each other.

NOW, if the difference of attraction of the moſt and leaſt refrangible rays were, in all mediums, proportioned to the whole attraction of the mean refrangible ray, it would be impoſſible to produce refraction without colour*. But ſubſequent experiments have proved, that this ſuppoſed general law of refraction does not hold in nature.

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* THIS at leaſt is true as to ſenſe in thoſe ſmall refractions which take place in teleſcopes and microſcopes; and it would be mathematically true in all caſes, if the angles of incidence and refraction were proportional. But as it is not the angles themſelves which are ſo, but their ſines, it is a miſtake to ſuppoſe that colourleſs refraction cannot be produced by large contrary refractions of the ſame medium, properly diſpoſed for the purpoſe.

In the inſtance before us, if we ſuppoſe the force with which glaſs attracts the red, green and violet rays to be repreſented by the numbers five, ſix and ſeven; then may the force with which the diſperſive fluid attracts theſe rays, be repreſented by the numbers four, five and ſix. For the reaſon why all the rays are equally refracted in their tranſition from one of theſe mediums into the other, is becauſe the rare medium has the property of refracting the violet rays more, and the red rays leſs, than the denſe medium, when the obliquity of incidence is ſo proportioned to their denſity, that the mean refrangible ray ſhall ſuffer the ſame refraction in both.

Now, in the caſe above ſtated, the attraction of the rare medium for the ſeveral rays, is ſo proportioned to the attraction of the denſe medium for theſe ſame rays, that the difference of theſe attractions is every where equal, and conſequently the refraction ariſing from theſe differences of attraction is alſo equal. Thus the green ray is attracted by the denſe medium with the force ſix, and by the rare medium with the force five, the difference of which is one; and there is the ſame difference between the attracting forces acting on the red and violet rays in the two mediums, being in one caſe the difference between five and four, and in the other between ſix and ſeven; ſo that the difference of attracting force, and conſequently the refraction ſuppoſed to ariſe from it, is the ſame in all the rays, being always that which will be produced by an attracting force, repreſented by unity.

If the diſperſive power of the rare medium, of which the priſm B C D is formed, be ſtill farther increaſed, the red rays will become the moſt refrangible, and the violet rays the leaſt refrangible; a law of refraction, which, as has been already explained, obtains when light is refracted in the confine of crown-glaſs and oil of turpentine, and of many other fluids.

If the mean refractive denſity of the diſperſive fluid, contained in the priſm B C D, be ſo far increaſed as to become equal to the mean refractive denſity of the glaſs priſm A B C, the mean refrangible ray will ſuffer no refraction in paſſing obliquely from the one medium into the other at the point G, but the violet ray will be refracted towards the perpendicular, and the red ray will be refracted from the perpendicular. The reaſon of which is, that the diſperſive medium refracts the violet ray more, and the red ray leſs than the other medium; ſo that the former may be conſidered as an equally denſe medium with the latter relative to the green ray, but more denſe relative to the violet ray, and leſs denſe relative to the red ray.

This caſe of refraction takes place in the confine of crown-glaſs and butter of antimony, when the latter is ſo far diluted as to have the ſame mean refractive denſity with crown-glaſs; that is to ſay, when both mediums equally refract the green ray, under equal obliquities of incidence.

These varieties of refraction will poſſibly be better comprehended by the aſſiſtance of diagrams.

Fig. 3. repreſents a priſm of crown-glaſs, which is entered perpendicularly by a red, green and violet ray, moving parallel with each other. As their incidence on the ſecond ſurface of the priſm is oblique, they will, in paſſing from the glaſs into air, be refracted from the perpendicular. This deflection of the light from its rectilineal courſe, is ſuppoſed to be produced by the perpendicular attracting forces, repreſented by the numbers five, ſix and ſeven. The violet ray will therefore be moſt deflected, the green next, and the red ray leaſt.

Fig. 4. repreſents a priſm of diſperſive fluid, which the three rays enter with the ſame degree of obliquity which they had before they emerged from the glaſs priſm. The attracting forces of the fluid for the ſeveral rays, are repreſented by the numbers four, five, ſix; and each of them will be deflected towards the perpendicular, in a degree proportioned to the force acting on it.

FIG. 5. repreſents the two priſms in contact, and the three rays entering the glaſs priſm perpendicularly, and emerging perpendicularly from the fluid; ſo that the only refraction they ſuffer in their paſſage, is in the confine of the two mediums.

AT the point of contact, the rays will be acted on by both mediums, with the ſame forces which they exerted when ſeparate. But theſe forces will act in oppoſition, and therefore the rays will only be affected by their difference; and as the difference of attraction of the two mediums is the ſame in all the rays, they will all be equally refracted. The red ray is attracted towards the glaſs by the difference between the forces four and five, the green by the difference between five and ſix, and the violet by the difference between ſix and ſeven, each of which differences is equal to unity, as repreſented in the figure.

IF the diſperſive power of the fluid, contained in the priſmatic veſſel, be diminiſhed by decreaſing the proportion of mercury or antimony which it contains, the violet ray will begin to be more refracted, and the red ray leſs refracted, than the green ray. But if that quality be increaſed, the contrary of this will happen; the red ray now becoming the moſt refrangible, and the violet ray the leaſt refrangible.

IF the diſperſive medium employed, be of that preciſe degree of ſtrength, which enables it to refract the green ray in the ſame degree in which it is refracted by crown-glaſs; in this caſe it has been aſſerted, that when light paſſes obliquely from the one of theſe mediums into the other, the green rays will ſuffer no refraction, but the red rays will be refracted from the perpendicular, and the violet rays towards the perpendicular. The reaſon of this will appear from inſpecting the three following diagrams.

Fig. 6. repreſents a priſm of crown-glaſs, in which the red, green and violet rays, at their emergence into air, are attracted, as before, with the forces five, ſix and ſeven.

Fig. 7. repreſents a priſmatic veſſel filled with butter of antimony, whoſe mean refracting force is equal to that of the crown-glaſs, ſo that the green ray is attracted by it with the force ſix. But in conſequence of its great diſperſive power, the red and violet are attracted, (we ſhall ſuppoſe for the ſake of round numbers) with the forces four and eight.

Fig. 8. repreſents the two priſms in contact, and conſequently acting in oppoſition to each other. Now, the force with which each of the mediums acts on the green ray, is repreſented by ſix; the difference between which being nothing, the green ray will proceed in its rectilineal courſe, as it would do in the ſame uniform medium.

But as the red ray is attracted by the crown-glaſs with a force repreſented by five, and by the diſperſive medium with a force equal only to four, it will, in paſſing out of the former into the latter, be deflected towards the crown-glaſs, by the difference between theſe forces, which is equal to unity.

The violet ray, on the contrary, is attracted by the crown-glaſs with the force ſeven, and by the diſperſive medium with the force eight, and will therefore be refracted towards the latter, in the ſame degree in which the red ray is refracted from it, as repreſented in the figure. It is a circumſtance worth remarking, that a particle of red light, and a particle of violet light, under preciſely the ſame circumſtances of expoſure to the action of groſs bodies, ſhould be urged in contrary directions.

I have tried theſe ſeveral caſes of refraction likewiſe with compound object-glaſſes, which ſhew the effect better than the priſms. Thus, if a plano-convex lens have its plane ſide turned ed towards a diſtant object, the rays will enter it, as to ſenſe, perpendicularly, and will therefore ſuffer no refraction. If the convex ſurface of this lens be brought in contact, with a fluid of leſs mean refractive denſity than the glaſs, but exceeding it in diſperſive power, in that degree which occaſions an equal refraction of all the rays, all theſe rays will then be converged to the ſame point, which are incident at the ſame diſtance from the axis of the lens. The focal diſtance of this compound lens will be greater or leſs in proportion to its radius of convexity, and to the difference of refraction between it and the fluid made uſe of. While the fluid is confined on one ſide by the plano-convex lens, let the lens which is brought in contact with it on the oppoſite ſide, have one of its ſides ground convex, and the other concave; the radii of their ſphericities being equal to the focal diſtance at which the rays are made to converge, by the refraction which takes place, when light paſſes from the plano-convex lens into the fluid. It is manifeſt that the light will now both enter into this compound lens, and emerge from it perpendicularly, and will therefore ſuffer no refraction, except in the confine of the convex ſide of the plano-convex and the diſperſive fluid, where all the rays are equally refrangible. A compound lens of this kind, is repreſented in the ninth figure, which, after what has been ſaid, will require no farther explanation; excepting only, that inſtead of being ſpherical, it is repreſented with that curvature which converges homogeneal rays, incident at all diſtances from the axis, to the ſame point. If the required curvature could be given to lenſes with ſufficient accuracy, this figure ſeems to repreſent as perfect a conſtruction of the object-glaſs of a teleſcope as can be deſired. But there is reaſon to think that a ſpherical figure may be communicated, not only much eaſier, but with greater accuracy than a ſpheroidal or hyperboloidal, which would be required; and even if this difficulty could be got over, there would ſtill remain a fundamental fault in the theory. Before relating the obſervations by which this was detected, it will be requiſite to explain the method of removing the ſpherical aberration, by a combination of convex and concave lenſes. For next to the indiſtinctneſs ariſing from the unequal refrangibility of light, this aberration, occaſioned by the ſpherical figures of lenſes, is the great obſtacle to the advancement of the powers of viſion.

Of the aberration from the ſpherical figure.

THIS ſubject has been treated of in all the variety of caſes which can occur in ſingle glaſs lenſes, by the great HUGENIUS, in his Dioptrics, a poſthumous work. He there demonſtrates that the quantity of this aberration is very different in different lenſes of the ſame focal diſtance, according to the convexities or concavities of their two ſides, and the manner in which theſe are expoſed to parallel rays.

IN convex lenſes, thoſe rays which paſs at a diſtance from the axis, are converged to a point nearer to the lens than its geometrical focus. The diſtance between the point at which the external ray of a pencil incident on a lens, interſects its axis and the geometrical focus, is called the linear aberration of that lens.

HUGENIUS demonſtrates, that when a plano-convex lens is expoſed to parallel rays, with its plane ſide towards them, this aberration will amount to four times and a half the thickneſs of the glaſs. By the thickneſs of a convex lens is meant its greateſt thickneſs in the middle, after ſubtracting its thickneſs, if it has any, at the outer edge; and by the thickneſs of a concave lens, is meant its thickneſs at the external edge, after deducting its thickneſs in the middle.

ON turning the convex ſide of the lens towards the light, the linear aberration will only exceed the thickneſs of the lens by one ſixth part.

When both ſides of a lens are convex, and the proportion of their convexities is as one to ſix, if the moſt convex ſide be expoſed to parallel rays, the aberration will exceed the thickneſs of the lens one fourteenth, which is the ſmalleſt poſſible aberration of any convex lens.

If it is required to increaſe the aberration, this may be done by grinding one ſide of the lens convex, and the other ſide concave, to a longer radius. Such a lens, with its concave ſide turned towards parallel rays, will have more aberration than any plano-convex or double convex lens of the ſame focal diſtance.

Hugenius proceeds to ſhew, that the ſame aberration is produced by concave lenſes as by ſimilar convex ones. When a plano-concave lens is expoſed to parallel rays, with its plane ſide outward, the external ray of the pencil, being produced backward after refraction, will interſect the axis of the lens nearer to it than its focus, by four times and a half the thickneſs of the lens. But if its concave ſide be expoſed to the parallel rays, the aberration will only exceed the thickneſs of the lens one [illegible] ~~fourteenth~~ part. A double concave, whoſe radii are as one to ſix, with the moſt concave ſide turned outward, diſperſes the rays with the leaſt aberration; and a concave meniſcus, with its convex ſide outward, produces more aberration than any plano-concave or double concave lens, of an equal focal diſtance.

These are ſufficient data for correcting the aberration from the ſpherical figure, in caſes where both a convex and concave lens are required, in the conſtruction of the compound object-glaſs.

Fig. 10. Let AB repreſent a convex lens receiving a pencil of rays from the object S, and converging rays incident near the axis, as ST, to the point F; and external rays, as SB, to the point

D; ſo that DF repreſents the greateſt linear aberration in this caſe.

Again, let GH (Fig. 11.) repreſent a concave lens, receiving the parallel rays SH, RK, which it refracts in the lines HX and KV. This ray KV being produced backward, will interſect the axis of the lens nearly at the point N, which is called the virtual focus of the concave; and the external ray HX produced backward, will interſect the axis in ſome point P nearer to the lens than its focus, PN being the linear aberration.

It may here be obſerved, that the convex is in that poſition which produces the leaſt aberration, and the concave in the poſition which produces moſt aberration. Hence, to render the aberrations DF (Fig. 10.) and PN (Fig. 11.) equal, the focal diſtance of the convex muſt be much ſhorter than that of the concave; and if the diſtances of the points F and N from the convex and concave lenſes be required to be the ſame, as repreſented in the figures, then muſt the object be placed much nearer to the convex. Hence the image of the near object S, is repreſented at the ſame diſtance from the convex ~~lens in fi~~gure tenth, as the virtual focus of the concave in figure eleventh, where it is repreſented as receiving parallel rays, which are ſuppoſed to come from an infinitely diſtant object.

Now, when the diſtance between K and N, which is the point from which parallel rays are made to diverge by the concave lens, is equal to the diſtance between T and F, which is the point to which rays iſſuing from S are made to converge by the convex; and when the aberrations DF and PN are alſo equal; I ſay, that in this caſe, if the two lenſes be placed contiguous, in the manner repreſented in the twelfth figure, parallel rays, incident on theſe lenſes, will be converged to the point S, without any aberration of the external ray.

For it is an axiom in optics, that if a ray of light after refraction be returned directly back to the point of incidence, it will be refracted in the line which was before deſcribed by the incident ray.

If therefore we conceive the whole of the light emitted from the point S (Fig. 10.), and converged by the convex lens towards the points D and F, to be returned directly back from theſe points, it will be accurately converged to the point S, whence it iſſued. Now, the parallel rays S H, R K, (Fig. 11.) after their emergence from the concave lens, in the lines H X, K V, are preciſely in the ſame relative ſituation, as the rays ſuppoſed to be returned directly back from F and D are in, at their incidence on the convex; and therefore, when theſe lenſes are placed contiguous, in the manner repreſented in the twelfth figure, parallel rays incident on the concave lens, and immediately after their emergence from it, entering the convex lens, will be accurately converged to the point S, without any aberration.

This, which is the moſt ſimple caſe, will ſuffice to explain the nature of that aberration, which ariſes from the ſpherical figures of lenſes, and a method of obviating it by combining a convex and concave.

The demonſtration is perfect as far as regards the external ray, which is here repreſented paſſing from the external part of the concave into the external part of the convex, in immediate contact with it; and if the ſurfaces of the two lenſes, which reſpect each other, were either in contact or parallel, it would be true with regard to all the rays. But as this is not the caſe, there ariſes a ſmall ſecondary aberration, the effect of which only becomes ſenſible in large apertures.

Hence may be underſtood the reaſon why the indiſtinctneſs ariſing from the ſpherical figures of lenſes, may, in the common achromatic teleſcope, be more nearly removed in thoſe conſtructions of object-glaſſes in which three lenſes are employed,

ployed, than in thoſe compoſed only of two; and alſo the advantages in this reſpect, which may be derived from introducing fluid mediums, which differ from glaſs in their mean refractive denſity, and in the quantity of aberration produced by their refractions. For it will be found upon computation, that when the fluid medium is rarer than glaſs, the aberration from the ſpherical figure is increaſed, and becomes greater in proportion as its denſity diminiſhes. Now, by making the denſity of the fluid medium approach nearer and nearer to the denſity of the glaſs with which it is in contact, we may increaſe the rarity of our refracting medium, or, which amounts preciſely to the ſame thing, diminiſh the difference of denſity of the two mediums at pleaſure.

It will appear from what has been explained, that the aberration from the figure cannot be corrected by interpoſing a diſperſive fluid between two convex lenſes, of a greater refractive denſity than the interpoſed fluid. For all the refractions being made the ſame way, tend to converge the external rays to points nearer the lens than its geometrical focus. Hence, when rare fluids are made uſe of to remove the aberration from the difference of refrangibility, ſome farther contrivance becomes neceſſary to correct the ſpherical aberration.

The moſt obvious way, and which on trial I found ſucceſsful, is to include the rare diſperſive fluid between two glaſſes, ground concave on one ſide and convex on the other, and thus form ſuch a concave as ſhall be required. By combining this with a convex, an achromatic object-glaſs may be formed, as repreſented in the ſixteenth figure. The objection to this conſtruction is, that one of the advantages ariſing from the uſe of fluids is given up, namely, the prevention of that loſs of light by reflection, which is a conſequence of the fluid being in immediate contact with the glaſs, whereas in the preſent caſe, the ſpace between the convex and concave is occupied by air.

ON this account I attempted to introduce a third medium, by filling this vacancy with a fluid of the leaſt diſperſive kind, and of leſs mean refractive denſity than the diſperſive fluid. For this purpoſe I employed ſometimes rectified ſpirit of wine, and ſometimes vitriolic æther; and by giving to the lenſes the proper degree of curvature, in which great variety may be introduced, I ſucceeded in forming object-glaſſes, in which both aberrations are removed, and hardly any more light loſt than in a ſimple object-glaſs.

HAVING gained this point, I now determined to try how far the aperture of the object-glaſs might be increaſed, without increaſing its focal length, expecting, at leaſt, to equal reflectors in this reſpect. But the firſt trials to execute object-glaſſes on this principle, though they left no reaſon to complain of want of ſucceſs, when compared with ſuch inſtruments as are now in uſe, ſurpriſed me with new phenomena, and new obſtacles to the perfection of the theory of teleſcopes, more unaccountable and perplexing than any I had before encountered. Theſe I ſhall now proceed to give an account of.

Of the imperfect correction of priſmatic colour which is obtained by a combination of mediums of different diſperſive powers.

I TOOK a compound object-glaſs of the conſtruction laſt mentioned, compoſed of three lenſes, two of them plano-convex and the other a meniſcus. The radius of convexity of one of the plano-convex lenſes is about four inches, and the convex ſide is turned towards the object. The radii to which both ſides of the meniſcus are ground, are about five inches, one ſide being convex and the other ſide concave. The concave ſide is made to reſpect the plane ſide of the above mentioned plano-convex, and the vacancy between them is filled with vitriolic æther. The third plano-convex lens is ground to a radius of ſix inches. Its convex ſide is turned towards the convex ſide of the meniſcus, and the vacancy between them is repleniſhed by a fluid of the requiſite degree of diſperſive power, which is confined by means of a ring of glaſs. Theſe lenſes are two inches and ſeven eighths of an inch in diameter, and the focal length of the compound object-glaſs is ten inches; the curvatures of the lenſes being ſo proportioned, as nearly to correct the aberration from the ſpherical figure.

The fluid I employed to remove the colour ariſing from the different refrangibility of light, was an eſſential oil, whoſe diſperſive quality I could eaſily increaſe or diminiſh, by mixing it with others differing in their diſperſive qualities, though of nearly the ſame mean refractive denſity; by which means, the correction of the error from the figure was not diſturbed, by varying the ſtrength of the diſperſive fluid. I now expected perfectly to remove the colour, by adding a little of one or other of the diſperſive fluids, as occaſion might require.

Before relating the event of this trial, it will be proper to explain the manner of examining the diſperſive power of fluids by means of lenſes, and of diſtinguiſhing when the colour is perfectly corrected.

When the image of a lucid point is formed in the focus of a ſimple lens, the violet rays are converged to a focus neareſt to the lens, and the deep red rays are converged to a focus at the greateſt diſtance from it. The conſequence of this is, that if this image be examined by an eye-glaſs nearer to the lens than is required for diſtinct viſion, it will appear ſurrounded with a red fringe, which is the prevailing colour of the leaſt refrangible rays; and if the eye-glaſs be placed at a diſtance beyond that which is required for diſtinct viſion, it will be ſurrounded with a blue fringe, which is the prevailing colour of the moſt refrangible rays.

The reaſon of this will appear more clearly from inſpecting the thirteenth figure, where the red rays appear outermoſt within the focus at A, and the violet rays appear outermoſt beyond the focus at B. Theſe colours may alſo be ſeen, when an image of any luminous object, as the ſun, is formed by a lens upon a white ground; and they will be ſo much the more conſpicuous, by how much the diameter of the lens is greater, in proportion to its focal diſtance.

JUST the reverſe of this will happen in a compound object-glaſs, if, in correcting the colour, the medium employed diſperſes more than it ought to do. A blue fringe will then appear round a luminous object, when the eye-glaſs is puſhed in; and a red fringe, when it is drawn out beyond what is neceſſary for diſtinct viſion.

IN this way the correction of the colour may be examined, and the qualities of refracting mediums inveſtigated, to an extreme degree of accuracy; yet the effect will be rendered ſtill more ſenſible, by covering half the object-glaſs. For when this is done, the colour produced by the uncovered half of the object-glaſs appears, without being mixed with that of the oppoſite ſide, even when the eye-glaſs is adjuſted to diſtinct viſion. Thus, in Fig. 13. the colours produced by both ſides of the lens, are mixed at the general focus F. But if the rays coming from one ſide be intercepted, thoſe which are refracted by the other ſide will appear in their proper colours. By theſe means, and by employing a very luminous object, ſurrounded by a dark ground, and a high magnifying power, the leaſt uncorrected colour may be rendered ſenſible.

MY firſt obſervations, which clearly proved the correction of colour which is obtained by the combination of two mediums differing in diſperſive power, to be only partial, were made in the ſummer of the year 1787, at Merchiſton.

I HAD, ſome time before, found it impoſſible to ſucceed, in this reſpect, with priſms compoſed of crown and flint-glaſs. But as I neither was able to make the phenomena ſo apparent by this method as with lenſes, nor had a command of priſms with that great variety of refracting angles neceſſary to put it yond all doubt, that the colour obſerved might not proceed from the angles of the priſms not being preciſely thoſe, which would render the correction of colour moſt perfect, I paid no farther attention to the ſubject at that time.

In examining the object-glaſs above mentioned, the object obſerved was a ſmall window in a white wall, at the diſtance of ſeveral hundred yards to the eaſtward of my ſtation, the ſun ſhining upon the wall from the weſt. The circumſtances of the phenomena, which I have extracted from memorandums written at the time of making the experiments, were as follow:

" *July* 28. 1787. In conſtruction A, (by this is meant the ten inch object-glaſs above deſcribed) when rendered as achromatic as poſſible, a purpliſh light appears on one ſide the focus, and a greeniſh light on the other."

In the next obſervation of this kind of incorrigible colour, the flame of Argand's lamp was uſed as an object, the great brilliancy of its light rendering the phenomena more conſpicuous. A cylinder of braſs was placed over the glaſs tube, which intercepted all the light, excepting what paſſed through a ſmall round hole oppoſite to the flame. I found no object preferable to this for the purpoſe, except the planet Venus, which cannot always be commanded. My obſervation mentions that " with the patent lamp, the colour is deep carmine within the focus, and greeniſh yellow without it."

Another memorandum on this ſubject runs thus: " Conſtruction 10. (by this is meant another object-glaſs, compoſed, like the former, of crown-glaſs, an eſſential oil, and ſpirit of wine, inſtead of æther, but a few inches longer than it, and more perfect) diſcovers a great deal of colour of ſome kind, in covering half the object-glaſs. The object, though ~~covered~~ coloured, is then more diſtinct than upon uncovering the other half; the colour is thus converted into miſtineſs. On altering the diſperſion of the fluid, the colour on one ſide alters from purpliſh violet to reddiſh violet, and on the other from greeniſh orange to greeniſh blue. As the diſperſion is diminiſhed, the red gains on the violet within the focus, and the greeniſh blue upon the orange without it, and *vice verſa*; and there is a conſiderable latitude, within which, varying the diſperſion, makes little difference in the diſtinctneſs."

As this laſt obſervation put it beyond doubt that an inveſtigation of the cauſe of theſe appearances was of the laſt importance to the improvement of optics, I now began to reaſon concerning them.

THE firſt conjecture that offered was, that this colour might ſomehow proceed from the ſurfaces of the convex glaſs lenſes, and the concave lenſes of diſperſive fluids, not correſponding at different diſtances from the centre, as the plane ſurfaces of priſms every where do. In order to examine what effect this might have, I procured two pieces of plate-braſs, with which I could cover the whole of the object-glaſs; and out of one of theſe I cauſed a ring, of a quarter of an inch in breadth, to be cut towards the centre, and out of the other, a ring of the ſame breadth, cloſe to the circumference. For I perceived that, if the colour aroſe from the cauſe above mentioned, its appearance ought to be different through theſe two rings, when there is an accurate correction of colour in that part of the object-glaſs, which is equi-diſtant from the centre and the circumference. But upon trying the experiment, the ſame purple and green colour appeared through both theſe rings, as through the whole object-glaſs, and the colours lay in the ſame order in both caſes. My remark upon this experiment is in the following words: " Upon trying with a ring either external or internal, the appearances remain the ſame, as when the whole aperture is uſed; which ſeems to prove that this colour ariſes from the diſperſion not being proportional, and not, as was ſuppoſed, from the ſurfaces not correſponding. It is evidently the greateſt bar to increaſing the aperture, and giving high powers; there is only a partial correction of colour; the differently refrangible rays cannot all be converged to one focus."

THE next method that occurred to me of determining the point in queſtion was more deciſive. This was to obſerve whether any of this green and purple colour appeared through the moſt perfect kind of achromatic object-glaſs above deſcribed, and repreſented in the ninth figure, in which there is only one refraction. This I found to be the caſe; and therefore conſidered myſelf as in poſſeſſion of ſufficient authority for concluding, that the theory advanced by Mr DOLLOND, and generally received, was defective. For with the large aperture and high power made uſe of in theſe experiments, the colour that appears in viewing a bright object is not weak and hardly ſenſible, but a beautiful bright purple inclining to crimſon, and a ſtrong full green, and theſe in ſuch a quantity as evidently to be the obſtacle to increaſing the aperture of the object-glaſs.

THIS was the concluſion I was then led to, and which I have found confirmed by numerous experiments made ſince. But before entering farther on the ſubject, it will be neceſſary to explain what is meant by different mediums not diſperſing the heterogeneal rays of light proportionally.

LET A B and C D (Figures 14. and 15.) repreſent the ſurfaces of two mediums, both of which equally refract the mean refrangible ray. This we ſhall ſuppoſe to be the green ray, though, in this explication, it is not material which is called the mean refrangible ray. The angles of incidence K G L, M R N, will then be equal, and the angles of refraction of the green ray HGg, $PR\gamma$, will alſo be equal in both theſe mediums.

LET one of theſe mediums C D exceed the other A B ſo much in diſperſive power, as to make the difference of the angles of refraction of the green ray, and extreme violet ray, in the medium C D, double of what it is in the medium A B; that is to ſay, the angle $\upsilon R\gamma$ double the angle νGg. Then if the difference of the angles of refraction of the green ray and deep red ray, in the medium C D, be alſo double of the difference of the angles of refraction of theſe rays in the medium AB, that is to ſay, the angle $\gamma R \varrho$ double the angle gGr; I ſhould ſay that the two mediums diſperſed theſe three kinds of rays, namely the red, green and violet rays proportionally. But if, when the difference between the angles of refraction of the green ray, and extreme violet ray, in the medium CD, is double of what it is in the medium A B; the difference of the angles of refraction of the green ray, and deep red ray in the medium C D, ſhall be found to exceed the difference between the angles of refraction of theſe rays, in the medium A B, only one half, for example; then I would ſay that the two mediums do not diſperſe theſe differently refrangible rays proportionally.

For in this caſe the medium C D diſperſes or ſeparates the green ray, and extreme violet ray, twice as much as the medium A B does; whereas the ſeparation of the green ray, and deep red ray, in this ſame medium C D, exceeds only by one half their ſeparation in the medium A B.

It is farther manifeſt, that the red, green and violet rays cannot be rendered parallel by any combination of the refractions of the two mediums, upon the laſt mentioned ſuppoſition. The whole refraction, through a priſm compoſed of the medium C D, may be ſuch as to give exactly the ſame inclination of the red and violet rays, which a priſm compoſed of the medium A B does, when both rays ſuffer a greater refraction through the latter; and therefore both theſe rays may be equally refracted and converged to the ſame point by means of a convex lens of the leaſt diſperſive medium AB, and a concave lens duly proportioned to it, formed of the moſt diſperſive medium C D.

But if we now add to theſe the green ray, it is evident that it too cannot be refracted parallel with the red and violet rays.

For when the whole refraction of the leaſt diſperſive medium AB is ſuch as juſt to unite the red and violet rays, the green ray, which is more refracted by this medium A B, in proportion to the whole refraction of the red and violet rays in the medium A B, than it is refracted by the diſperſive medium C D, in proportion to the whole refraction of the red and violet rays in the medium C D, will, when the red and violet rays are united by contrary refractions through theſe two mediums, be refracted too much; the balance of refraction being always, in this caſe, in favour of the leaſt diſperſive medium; and therefore the green light will emerge from this compound refraction more refracted than the united red and violet light, and the inclination of the emergent green light to the emergent united red and violet light, will be greater or leſs according as the ratio in which the red, green and violet light are ſeparated by the refraction of the two mediums, approaches more or leſs to equality. What this inclination amounts to, in any particular inſtance, muſt be determined by experiment.

Hence if the caſe of unproportional diſperſion, above ſtated, ſhould be found to hold true in fact, we ſhall arrive at this new truth in optics, That though in the refraction of a pencil of ſolar light, made in the confine of any medium, and a vacuum, the deep red rays are always the leaſt refrangible, and the violet rays are always the moſt refrangible; yet it depends entirely on the ſpecific qualities of the medium, which ſhall be the mean refrangible ray; the very ſame ray, which in the refraction through one medium is the mean refrangible ray, being found in others among the leſs refrangible rays. For it is manifeſt that the ray which biſects the angle formed by the moſt and leaſt refrangible rays, and falls in the middle of the coloured ſpectrum, is to be accounted the mean refrangible ray.

Thus, in Fig. 14. the green ray Gg is the mean refrangible. But in Fig. 15. the green ray Rγ is found among the leſs refrangible rays, and ſome other ray, R ω, which is one of the more refrangible rays in the medium A B, is the mean refrangible ray in this medium C D.

THE moſt obvious way of examining the optical properties of different mediums, is by means of priſms. But I have not found this method either ſo eaſy or ſo accurate as that by means of lenſes, which has been already explained. It has been ſhewn that the image of a lucid point (ſee the thirteenth figure) is every where, between the lens and that point where the rays croſs, ſurrounded with a fringe of the colour of the leaſt refrangible rays; and that every where beyond the point of croſſing, the image is ſurrounded with a fringe of the colour of the moſt refrangible rays; and that theſe colours appear more diſtinctly at the focus itſelf, when one half of the lens is covered. Hence, in order to determine which rays are the moſt or leaſt refrangible, after refraction through any lens whether ſimple or compound, it is only neceſſary to examine the colours of theſe fringes, which is the more eaſily done, as they are greatly magnified by the eye-glaſs.

IN ſingle lenſes, the fringe within the focus, which is compoſed of the leaſt refrangible rays, will always be found to be of a red colour, with a mixture of orange; and the fringe beyond the focus, compoſed of the moſt refrangible rays, will be found to be of a blue colour. Theſe are the colours which, it is well known, are produced by ſimple refraction, made in the confine of every known medium and a vacuum.

FROM what hath been already related, it appears, that colour is likewiſe produced in what has been termed achromatic refraction, though it be leſs in quantity in proportion to the whole refraction; and the rays which are found moſt and leaſt refrangible, in theſe two caſes, differ very widely.

IN a compound object-glaſs, formed of a concave, which diſperſes the rays in a greater degree, and a convex, which diſperſes the rays in a leſs degree, there was always found, when the correction of colour was rendered the moſt perfect poſſible, a fringe of purple within the focus, and a fringe of green beyond the focus; and theſe coloured fringes appeared, whether the concave conſiſted of flint-glaſs or of an eſſential oil. Therefore, in this kind of compound refraction, the rays of light, when their union is rendered the moſt perfect poſſible, emerge differently refrangible; and the rays which emerge moſt refrangible, have the property of exciting in us the idea of a green colour; and the rays which emerge leaſt refrangible, have the property of exciting in us the idea of a purple colour.

WHEN, for the ſake of brevity, I ſpeak here, or elſewhere, of the union of the red and violet rays, as if it were performed by a ſingle refraction, whereas, in general, the moſt that can be effected is to render them parallel by oppoſite refractions, I would be underſtood to refer to the moſt ſimple and perfect caſe of achromatic refraction, in which the extreme red and violet rays are really equally refracted, and conſequently united, by a ſingle refraction, as already explained in the references to the fifth and ninth figures.

THE fringe of purple light is formed, in part, by an union of the red and violet rays, which in ſimple refraction differ moſt in refrangibility, but which are here equally refrangible; and partly, of the united orange and indigo light, which are alſo united, and form the ſecond order of coloured light in this ſecondary ſpectrum.

THE green fringe is compoſed in part of the homogeneal green rays, which, in common refraction, are the mean refrangible, or nearly ſo, but are now the moſt refrangible of all. The remainder of this green fringe is formed by an union of the yellow and blue rays, compoſing what may be termed an heterogeneal green.

IT will appear from the foregoing ſtatements, in what manner this diſpoſition of the rays is a neceſſary conſequence of the concave and convex lenſes being compoſed of mediums which do not diſperſe the rays proportionally, as before explained. But the matter will be beſt underſtood, by recurring to the caſe above mentioned, of ſingle achromatic refraction. Thus I continue to denominate it, though the Society will perceive that this term *achromatic*, is here uſed with manifeſt impropriety; and will alſo make proper allowance for the ſenſe in which I have employed the term *homogeneal light*, in conformity to the common language of optics.

It was formerly aſſerted, that when two mediums differ in mean refractive denſity, and the diſperſive power of the rare medium exceeds that of the denſe medium in a certain proportion, light of all colours will be equally refracted in the confine of the two mediums; and it is true that the red and violet rays will be equally refracted, and the rays of other colours as nearly ſo as by any combination of two mediums of different diſperſive powers. But on account of the two mediums not attracting, and conſequently ſeparating the rays of different colours in a given ratio, the ſame green and purple-coloured fringes appear in an object-glaſs of this kind, as in one in which oppoſite refractions are employed; ſo that in the refraction which takes place in the confine of two ſuch mediums, the rays of light are ſtill unequally refrangible. But inſtead of the degree of refrangibility being, as in common refraction, according to the order of the colours, red, orange, yellow, green, blue, indigo, violet, the priſmatic ſpectrum is, as it were, doubled, the rays being, at the ſame time, compreſſed nearer to each other; and their degrees of refrangibility being now according to the following order: Red and violet united, the leaſt refrangible; next to theſe in refrangibility, the orange and indigo united; then the united yellow and blue; and, laſtly, the homogeneal green rays, which are the moſt refrangible.

Of the perfect correction of the aberration ariſing from the unequal refrangibility of light.

THIS fact now eſtabliſhed on the fulleſt evidence, that the divergency of the heterogeneal rays is not to be removed by a combination of crown-glaſs with flint-glaſs, or with thoſe diſperſive fluids employed in the object-glaſſes, with which the experiments above related were made, diſcovered a moſt important problem in optics, namely, the entire removal of the aberration from the difference of refrangibility of light, by any combination of mediums whatever.

THIS problem, it was evident, was only to be attempted by again having recourſe to the volume of nature, and ſearching out the hidden qualities of refracting mediums. Though in all the compound object-glaſſes which were examined, after being rendered as achromatic as poſſible, the ſame colours appeared, and in the ſame order; yet every trial could only be conſidered as ſpeaking for itſelf, if the expreſſion may be allowed. The experiments were indeed numerous, and will, I hope, be found to have been made with ſufficient care and attention; yet to have formed from them any general concluſion, that in every endeavour to unite the rays of all colours, by a combination of mediums differing in diſperſive power, the green rays will emerge moſt refracted, and the red and violet leaſt refracted, as above explained, could only ſerve to prevent farther inveſtigation, by repreſenting the perfection of the theory of optical inſtruments by refraction as a deſperate attempt.

THE order in which I proceeded farther to explore this ſubject was the following:

HAVING found fringes of colour, as above deſcribed, in combinations of crown-glaſs with the eſſential oils, and in combinations of crown-glaſs and flint-glaſs, when the refraction is rendered as colourleſs as poſſible, I began by trying other diſperſive mediums, which owe this property to different metallic or ſaline particles with which they are impregnated, in hopes of finding ſome diſperſive medium, which might ſeparate the differently refrangible rays in the ſame proportion in which crown-glaſs does, and thus afford a method of refracting all of them alike, and conſequently without colour. But I was diſappointed. The compound object-glaſſes, formed of a variety of diſperſive fluids and crown-glaſs, exhibited green and purple fringes, as before, which proved the diſperſive power of the two mediums not to be proportional.

My next ſtep was to vary the combination by rejecting glaſs entirely as a refracting medium, and only employing it to confine the fluids. As a fluid medium was here to be uſed as a convex lens, thoſe which had been found leaſt diſperſive, were to be made choice of. Accordingly, water, ſpirit of wine, nitrous and vitriolic æther, and all the limpid indiſperſive fluids I could come at, were made trial of. But ſtill the reſult was the ſame. The green and purple fringes appeared, on covering half the object-glaſs.

I then ſubſtituted ſome other of the more perfect indiſperſive kinds of glaſs inſtead of crown-glaſs; but with no better ſucceſs.

Next I combined two eſſential oils, both of them more diſperſive than crown-glaſs, but differing ſo conſiderably in this reſpect between themſelves, that the leſs diſperſive could be uſed as a convex, while the other was ſo diſpoſed as to perform the office of a concave. For it will eaſily be underſtood, that lenſes of any kind may be formed of fluid mediums, by including them between glaſſes, which have one ſide formed convex, and the other concave, to the ſame radius, and thus ſerve merely to confine the fluids, without producing themſelves any effect in refracting the light. If a flat ſide is wanted, a piece of plain glaſs with parallel ſides muſt be uſed, and in concave lenſes of this kind, the farther contrivance of a glaſs-ring to confine the fluid is required.

The effect of the above combination, which was of oil of turpentine with a mineral oil, I immediately perceived to be different from what was obſerved in the preceding trials. The green and purple fringes ſtill appeared, and they lay in the ſame order as before; but their breadth was greatly diminiſhed, I judged about one half.

This new fact was the only fruit of this laſt ſet of experiments, which were attended with much trouble and loſs of time. For to make them with the requiſite degree of preciſion, pains muſt be taken, not only to get the refraction as colourleſs as the qualities of the mediums will admit, but alſo to compute the error from the ſpherical figure, and procure lenſes accurately ground to the ſpheres which are required. Unleſs theſe points are duly attended to, accuracy in the reſults is not to be expected.

I now conſidered how this diminution of the breadth of the coloured fringes, obſerved in the laſt mentioned experiment, might beſt be turned to account. In the firſt place, it was obvious, that an object-glaſs, formed by a combination of the mediums uſed in that experiment, would have an advantage over others, in which the correction of the aberration from the difference of refrangibility is more imperfect. But as this fault, though greatly diminiſhed, would ſtill prevent the uſe of high magnifying powers, I weighed the circumſtances more attentively, and the matter appeared to me in the following light:

A convex lens, formed of the leaſt diſperſive of the two eſſential oils, being ſo combined with a concave lens, formed of that which is moſt diſperſive, as to unite the red and violet rays, leaves fringes of uncorrected colour, much narrower than thoſe produced by compound object-glaſſes of the ſame focal diſtance, formed by a combination of either of theſe fluids with glaſs. Hence I was led to conclude, that if I took an achromatic convex lens, compoſed of the two eſſential oils, and combined it with an achromatic concave lens of a longer focal diſtance, compoſed of crown-glaſs and either of the eſſential oils, I ſhould be able, through ſuch a double compound object-glaſs, to converge the rays to a focus, without any aberration whatever from the difference of refrangibility of light. For if the compound convex and compound concave are properly proportioned to each other, the ſecondary ſpectrums, or fringes of green and purple, may be rendered of the ſame breadth in both lenſes; and from the obſervations before related, this will happen when there is a conſiderable balance of refraction in favour of the convex lens. For it is compoſed of materials which form a much narrower ſecondary ſpectrum, under an equal refraction of the whole pencil, than thoſe mediums do, of which the compound concave is formed.

THIS will be underſtood, by attending to what takes place in the refractions of light through the lenſes, without again recurring to the more ſimple caſe of priſms.

FIG. 17. repreſents a compound concave lens, formed of a concave lens of glaſs, and a convex ~~concave~~ lens of a diſperſive fluid, but of a ſhorter focus than the concave lens, and ſo proportioned as to produce a refraction as free from colour as can be obtained by a combination of theſe two mediums. This lens being expoſed to parallel rays, will make them diverge, after refraction, from its virtual focus, and the united red and violet rays will be the leaſt refracted, and will be inclined in a certain angle to the green rays which are moſt refracted, as repreſented in the figure.

FIG. 18. repreſents a compound convex lens, formed of a convex of an eſſential oil, which diſperſes the rays in a leſſer degree, combined with a concave of an eſſential oil, which diſperſes the rays in a much greater degree. The convexity of this compound lens is ſuch, as to unite, at a convenient diſtance, rays diverging as from the virtual focus of the compound concave. The whole refraction through the convex is conſequently much greater than through the concave. But notwithſtanding this, the angle formed by the green ray with the united red and violet rays, is repreſented equal in the two lenſes. For as the effect of the mediums of which the compound concave is formed, is to ſeparate the united red and violet rays from the green rays, much more than thoſe of which the compound convex is formed, when the refraction of the pencil is equal, it becomes neceſſary, in order to render this ſeparation equal in both lenſes, to diminiſh the refraction through the concave.

An object-glaſs formed of ſuch a compound concave and compound convex, appears more complicated than it is in reality. It may be rendered complete without employing more than two fluid mediums and three glaſs lenſes, which were found neceſſary merely to correct the aberration from the ſpherical figure. Thus, in the nineteenth figure, the two compound lenſes are repreſented in contact; and it is manifeſt, that the pieces of plain glaſs with parallel ſides, which were neceſſary to confine the fluid when the lenſes were ſeparate, are now uſeleſs; for it is the very ſame fluid which is on both ſides of theſe plain pieces of glaſs; and as they produce no effect in refracting the light, they are better removed, as repreſented in this figure.

Parallel rays incident on the concave lens, are here repreſented converged to a focus, without any aberration whatever. This is a neceſſary conſequence of what hath been related concerning the properties of the refracting mediums, of which this compound object-glaſs is formed.

In both the concave and convex, the red and violet rays are united, and form the leaſt refrangible rays, and in both, the green rays are the moſt refrangible. But as the angle formed by theſe moſt and leaſt refrangible rays, would be much greater in the concave if the whole refractions were equal, the whole refraction is here repreſented to be preciſely that which is requiſite for giving the ſame inclination of the green rays to the united red and violet rays, which takes place after refraction through the convex. Hence, as theſe refractions are equal and oppoſite, they deſtroy each others effect. The rays proceed after refraction without any divergency from unequal refrangibility; and the aberration from the ſpherical figure being alſo corrected by means of the concave glaſs lens, which is more denſe than either of the fluids, they are converged to the ſame point.

The conſtruction repreſented in theſe figures, is not, however, the moſt perfect and convenient for the purpoſe. The beſt method is to divide the concave glaſs neceſſary for removing the ſecondary colour, by making two of the lenſes, or all three of them, concave meniſcuſes. But throwing the whole concave glaſs into one lens, and exhibiting the compound convex and compound concave lenſes ſeparately, anſwers beſt the preſent purpoſe of explaining the principle on which the aberration from unequal refrangibility may be totally removed. On the ſame account, the difference of the diſperſive power of the two fluids, is repreſented greater than it is in reality.

Having completed an object-glaſs of this kind, I carefully examined whether any colour was yet diſcernible. For though the red and violet and green rays were now united, it was a thing poſſible, that rays of other colours might ſtill have a ſmall inclination to theſe. But I could diſcover no colour by the moſt rigid teſt; and therefore conclude the refraction of all the rays of the ſpectrum to be now equal. If there be any deviation from this equality of refraction, it is inſenſible; and inſenſible errors, in thoſe caſes where ſenſe is the only judge, may be accounted no errors at all.

I HAD now attained the object I was in ſearch of, namely, a method of refracting equally all the rays of which light is compoſed. Nor was the conſtruction of object-glaſſes for teleſcopes, which it afforded, liable to any very material objection. The principal inconvenience aroſe from the neceſſary depth of the ſpheres of the lenſes required, which was now the only remaining obſtacle to ſhortening the refracting teleſcope at pleaſure.

IN the firſt trials I made to diſcover a diſperſive medium which ſhould ſeparate the rays in the ſame proportion in which glaſs does, I was in hopes of perfect ſucceſs, and therefore not at all curious in obſerving the breadths of the coloured fringes, ſtill hoping that the next trial might afford a refraction without any colour whatever. I therefore thought it expedient to repeat ſome of them, with greater attention to that circumſtance.

THE firſt fluid I happened to make trial of, was a metallic ſolution with a mixture of marine acid. Upon comparing an object-glaſs, rendered achromatic by this ſolution, with another as nearly ſimilar to it as poſſible, in which an eſſential oil was employed for that purpoſe, the breadth of the coloured fringes appeared indiſputably much narrower in the former than the latter *. I repeated the experiment frequently, to enable me to judge of the proportion of focal diſtance of a compound concave, neceſſary to correct this ſecondary colour, upon the principle which hath juſt been explained. Upon a comparative trial, I found it better to form the compound convex of a combination of this fluid and glaſs, than of a combination of two eſſential oils. The convex was not only ſhorter itſelf, with the ſame depth of ſpheres, but required a ſhallower compound concave

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* THE cauſe, at that time unknown, was, that the ſolution happened to contain an unuſual proportion of the marine acid; as will be underſtood from what follows.

concave lens to remove the colour entirely. The colour may be totally removed, and the aberration from the figure corrected, by a concave which lengthens the focal diſtance of the convex only one third.

FROM what hath been explained reſpecting the total correction of colour, it will be underſtood, that if the concave lengthens the focal diſtance beyond what is required, fringes of green and purple ought to begin to appear in an inverted order. This, which may be ſtyled the *experimentum crucis* in this matter, I now had it in my power to try without difficulty. The reſult turned out exactly as I expected. Upon applying a compound concave, which nearly doubled the length of the compound convex, a fringe of green appeared within the focus, and a fringe of purple beyond it, which ſets the theory of the correction of this ſecondary colour in the moſt ſatisfactory light.

THE compound concave in this and all the preceding experiments, was formed of glaſs and an eſſential oil.

I NOW happened, merely with a view of diverſifying the experiment, to apply a compound concave, formed of glaſs combined with the muriatic acid, which has been mentioned as a fluid poſſeſſing a conſiderable degree of diſperſive power. This opened a new and unexpected ſcene. The colours appeared in the ſame order as in the laſt experiment, but the fringes were ſo very broad as greatly to ſurpriſe me, and create a ſuſpicion that every thing was not as I had hitherto taken for granted. Without delay I included ſome of the marine acid between two convex lenſes, whoſe radii were duly proportioned to the diſperſive power of that fluid, for the purpoſe of correcting the colour. Upon applying an eye-glaſs I found my ſuſpicion verified. The fringes of green and purple appeared nearly of the uſual breadth, but in an inverted order, there being now a green fringe within the focus, and a purple fringe beyond it. I was the better pleaſed at being thus led to the detection of this ſingular property of the acid of ſea-ſalt, becauſe, in making the ſame experiment before, this inverſion of the order of the colours had entirely eſcaped me. I was then examining it, to find whether it diſperſed the ſeveral orders of rays, in the ſame ratio in which glaſs does; and being ſatisfied that it did not, from obſerving the green and purple fringes, as in other combinations, a circumſtance ſo little looked for, as the inverſion of the order of the colours, did not ſtrike me.

THIS obſervation affords a remarkable exception to what I had begun to conſider as very probably a general law of nature. In the refraction which takes place in mediums of the leaſt diſperſive kind, the green rays, or rather perhaps the rays in the confine of green and blue, are the mean refrangible, and theſe ſame rays, in the more diſperſive mediums, were always found among the leſs refrangible rays; and hence when, by a proper combination of two ſuch mediums, the red and violet rays are united, theſe united red and violet rays conſtitute the leaſt refrangible rays, and the green conſtitute the moſt refrangible rays, as before explained.

BUT in the muriatic acid, the caſe is juſt the reverſe of this. Then the green rays, which in mediums that diſperſe the leaſt, are the mean refrangible, and which in eſſential oils and metallic impregnations are found among the leſs refrangible, appear amongſt the more refrangible. Whence in ſuch a combination of the muriatic acid and an indiſperſive medium as ſhall unite the red and violet rays, theſe united red and violet rays emerge moſt refrangible, and the homogeneal green rays emerge leaſt refrangible, being juſt the reverſe of what takes place in combinations of crown-glaſs with flint-glaſs, or with eſſential oils, or ſaturated metallic ſolutions.

THIS unuſual property of the marine acid does not, however, ſeem to admit of any immediate application to the improvement of optical inſtruments. It is true that, inſtead of having recourſe to a compound concave for correcting the ſecondary colour, this may be effected by a compound convex, which, inſtead of lengthening, will ſhorten the focal diſtance of the compound object-glaſs. But in a conſtruction of this kind, the correction of the ſpherical aberration would be attended with more difficulty.

HAVING thus found an exception to the general reſult of my former experiments, which was, that thoſe rays which in the leaſt diſperſive mediums conſtitute the mean refrangible rays, are in more diſperſive mediums found amongſt the leſs refrangible rays, it ſeemed not improbable that diſperſive mediums might exiſt, which would ſeparate the differently coloured rays exactly in the ſame proportion in which they are ſeparated by indiſperſive mediums.

I HAD now indeed got hold of a pretty ſure clue to lead me to mediums poſſeſſed of this property. It will appear from what has been ſaid concerning attraction, that when in a metallic ſolution or an eſſential oil, which ſeparate the red and violet rays in the ſame degree in which they are ſeparated by the marine acid, the green rays are found amongſt the leſs refrangible rays in the former fluids, and amongſt the more refrangible in the latter fluid, the cauſe of this difference muſt be, that the green light is more attracted by the marine acid than by eſſential oils or metallic ſolutions, when the attraction for the red and violet light is the ſame in all theſe mediums.

HENCE it ſeemed reaſonable to conclude, that in a medium compounded in a due proportion of the particles compoſing theſe two kinds of diſperſive mediums, the attraction for the green rays would be in an intermediate degree, and might be rendered the ſame, in proportion to the attraction for the red and violet rays, which obtains in crown-glaſs and other indiſperſive mediums.

IT might be found a matter of no ſmall difficulty to unite the eſſential oils with the marine acid, ſo as to form a colourleſs tranſparent fluid. But nothing can be better adapted for this purpoſe than metallic ſolutions.

I FIRST made trial of butter of antimony, and found the reſult to be what I expected. On increaſing the proportion of muriatic acid, the fringes of green and purple grew narrower and narrower till they entirely diſappeared, and if more was then added they re-appeared in an inverted order. I tried the ſame thing with a ſolution of crude ſal ammoniac and mercury ſublimate. If the ſolution contains a certain proportion of theſe two ſubſtances, the rays of all colours emerge from the compound object-glaſs equally refracted. If the proportion of the ammoniacal ſalt, and conſequently of the muriatic acid which it contains, be increaſed, the green rays, which were the mean refrangible in the diſperſive fluid, as well as in crown-glaſs, draw nearer to the violet, making a part of the more refrangible half of the ſpectrum, and conſequently emerge leſs refracted than the united red and violet rays, and are converged to a focus at a greater diſtance from the object-glaſs; ſo that the green fringe now appears within the focus, and the purple fringe beyond it. But on increaſing the proportion of mercurial particles, theſe ſame green rays ſhift their ſituation to the leſs refrangible half of the ſpectrum, which appears from their now emerging moſt refracted, and being converged to a point nearer to the object-glaſs than the united red and violet, whoſe refrangibility does not appear to be affected by theſe admixtures which occaſion ſuch remarkable fluctuations in the refrangibility of the green rays and other intermediate orders. It may poſſibly ſeem ſtrange at firſt view, that the green rays ſhould emerge moſt refracted from the compound object-glaſs, when their refrangibility in the diſperſive medium is diminiſhed, and leaſt refracted under the contrary circumſtances. The cauſe of this is, that the principal refraction of the compound object-glaſs is performed by the indiſperſive convex lens, which is oppoſite to the refraction produced by the diſperſive concave.

It was formerly obſerved, that in the confine of a rare diſperſive medium, and a denſe indiſperſive medium, there may be a ſingle refraction, in which all the rays are equally refrangible; and it has ſince been explained with what limitation this is to be underſtood, in conſequence of the unproportional diſperſion which generally takes place in ſuch mediums; of which I was then ignorant. The explanation which refers to the ſecond, third, fourth and fifth diagrams, and to the object-glaſs repreſented in the ninth figure, is to be conſidered as ſtrictly juſt, when, in the fluid employed, the metallic particles are ſo far diminiſhed, and the particles of marine acid ſo far increaſed, as to render the refraction of the ſeveral orders of rays proportional in both mediums.

I have got an object-glaſs of this kind, which is repreſented in the twentieth figure. There are two refractions in the confine of glaſs and the fluid, but not the leaſt colour whatever. Hence it is manifeſt that in the refraction which takes place in the confine of glaſs and this fluid, and which, on account of the difference of their denſities, is very conſiderable, there is no unequal refrangibility of light. The rays of different colours are bent from their rectilineal courſe with the ſame equality and regularity as in reflection.

As cuſtom has already appropriated the word *achromatic* to that kind of refraction in which there is only a partial correction of colour, in order to avoid confuſion, I ſhall beg permiſſion to diſtinguiſh this entire removal of aberration by the term *aplanatic*[*], till a better can be thought of.

Before cloſing this enquiry concerning the optical properties of tranſparent ſubſtances, I examined more minutely than I had done before, the qualities of the other mineral acids. The nitrous acid, when of the ſame mean refractive denſity as the

[*] From the Greek α privative, and the verb Πλανάω.

the marine acid, does not diſperſe the red and violet rays quite ſo much. The green ray, as in the marine acid, is found among the more refrangible rays; but it approaches nearer to the place of the mean refrangible ray in the nitrous acid than in the marine. The green ray is alſo nearer to the place of the mean refrangible ray, than it is in eſſential oils or in ſaturated metallic ſolutions; and therefore the nitrous acid appears by theſe experiments to diſperſe the ſeveral orders of rays more nearly in the ſame proportion in which crown-glaſs does, than any uncompounded diſperſive medium, and would, I have no doubt, do ſo exactly, if ſlightly impregnated with mercury, though this I have not tried.

THE vitriolic acid is ſcarcely to be claſſed among diſperſive mediums. The following experiment is the laſt I made on the ſubject. In a very good object-glaſs, of that kind before deſcribed, in which ſpirit of wine is one of the mediums employed, I ſubſtituted ſucceſſively for this ſpirit the vitriolic acid and a ſolution of fixed alkaline ſalt, both of them of nearly the ſame mean refractive denſity as the ſpirit of wine. Theſe three fluids, although they differ ſo widely in their chemical properties, have their optical properties ſo nearly alike, that I found it difficult to determine which was the medium employed. For when the ſecondary colour is not corrected, as was the caſe in this object-glaſs, the change of colour produced in the green and purple fringes to render it apparent, muſt be conſiderable, a ſlight ſhade of difference not being eaſily diſtinguiſhable. I therefore repeated the trial with an object-glaſs, in which this green and purple light is totally removed; and then both the vitriolic acid, and the ſolution of fixed alkali, when of equal mean refractive denſity with ſpirit of wine, appeared very ſenſibly more diſperſive than the ſpirit. The difference in this reſpect between the acid and the alkali was ſcarcely to be diſtinguiſhed; and the effect of a ſolution of cauſtic alkali appeared to be nearly the ſame as that of mild alkali of equal denſity. By ſimilar trials, the phoſphoric and acetous acids were found to be conſiderably more diſperſive than ſpirit of wine.

ALTHOUGH theſe experiments with compound object-glaſſes of very large apertures, afford both the readieſt and moſt accurate method of inveſtigating the optical properties of refracting mediums, it would be both amuſing and inſtructive to repeat them with compound priſms. I could have wiſhed in particular, had my preſent ſituation been convenient for the purpoſe, to have taken the dimenſions of the ſecondary ſpectrum, under given angles of incidence and refraction. For by comparing theſe with the dimenſions of the primary ſpectrum, accurately aſcertained by Sir ISAAC NEWTON, the degree of ſuperiority of an object-glaſs compoſed of crown and flint glaſs, over a ſimple object-glaſs, and of one in which there is a regular refraction of all the rays, over both, might be aſcertained. At preſent, I can only ſtate the circumſtances of a compariſon I made between two compound object-glaſſes of equal apertures, but very unequal lengths. One was compoſed of crown-glaſs, ſpirit of wine and an eſſential oil. The focal length is about fourteen inches, and the aperture two inches. The other object-glaſs was of crown and flint-glaſs; its focal length thirty-two inches, and its aperture two inches. I had it for a good one of its kind, and upon examination found no particular defect in its ſtructure.

THE ſhort teleſcope has a manifeſt advantage in the night, eſpecially in viewing fine objects, ſuch as double ſtars of inferior magnitudes, where the uncorrected colour is leſs hurtful.

BUT I was ſurpriſed, on viewing an object in bright ſunſhine, to find conſiderably more of that miſtineſs which ariſes from the unequal refrangibility of light, than appeared in the long teleſcope. I therefore diminiſhed the aperture of the ſhort one to one inch and a half, and comparing them again, there appeared no more of this miſt in the one than in the other. I farther reduced the aperture of the ſhort one to one inch, when it became manifeſtly clearer than the long one, though, upon examining the coloured fringes, by covering half the object-glaſs, they ſtill appeared of ſuch a breadth as muſt neceſſarily hurt the diſtinctneſs.

I HAVE here given the reſult of this experiment as I find it noted down. Being made with no view to the determination of the point in queſtion, the accuracy neceſſary for that purpoſe was not obſerved. It would appear, however, from this groſs and indirect trial, that the aberration from unequal refrangibility would not differ very materially in theſe object-glaſſes, ſuppoſing their apertures and focal diſtances to be equal; though in one the partial correction of colour is effected by a combination of flint-glaſs and crown-glaſs, and in the other by a combination of crown-glaſs and ſpirit of wine, with an eſſential oil. If this aberration were exactly equal in both combinations, the miſty indiſtinctneſs proceeding from it ought to be the ſame in both object-glaſſes, when the apertures and magnifying powers applied, are as the ſquare roots of their reſpective focal lengths.

IT would appear that the aperture of an object-glaſs, compoſed of crown and flint-glaſs of thirty-two inches in focal length, ought not to exceed two inches, and therefore that three inches is too large an aperture for one of forty-two inches focal length; for the lengths in theſe two caſes ought to be as four to nine. In ſome teleſcopes of this latter kind, I have obſerved a great deal of uncorrected colour, which prevents them from bearing magnifying powers, in proportion to the aperture of the object-glaſs. It is indeed but ſeldom that the union of the differently refrangible rays is ſo perfect as the conſtruction admits. I have met with others in which the real aperture is ſo far contracted, by diaphragms placed within the tube, as ſcarcely to exceed two inches.

From inſpecting the tables of the lengths and apertures of teleſcopes with ſimple object-glaſſes, it will appear, that the required length for an aperture of two inches is about thirteen feet. This exceeds two feet and an half, the length given to an achromatic teleſcope, whoſe object-glaſs is two inches in diameter, between five and ſix times. The length of the ſtandard Hugenian teleſcope, whoſe aperture is three inches, is thirty feet. This is between eight and nine times the length of an achromatic teleſcope, the aperture of which is likewiſe three inches, and its length three and a half feet. But if the aberration from unequal refrangibility be diminiſhed to the ſame degree as in the thirty inch teleſcope, the length muſt be increaſed, from three and a half feet, to above five and a half. For its length muſt be to thirty inches, the length of the two inch aperture, as the ſquare of two to the ſquare of three, and then the teleſcope with the ſimple object-glaſs will only exceed it in length between five and ſix times as before.

The obſervations which have been mentioned put it beyond a doubt, that the limit to the apertures and magnifying powers of what have been improperly called achromatic teleſcopes, is the very ſame which limits the performance of teleſcopes with ſimple object-glaſſes, namely, the unequal refrangibility of light; and it would ſeem that the aberration from this cauſe may be diminiſhed, by a combination of lenſes of crown and flint-glaſs, between five and ſix times.

Sir Isaac Newton, by accurate experiments, hath determined the diameter of the leaſt circular ſpace within which parallel rays of all kinds can be collected by a ſimple lens, to be one fifty-fifth part of the diameter of the aperture of the lens. If the aberration from unequal refrangibility in a compound object-glaſs, vitiates the diſtinctneſs leſs than in a ſimple object-glaſs, in the proportion of one to ſix, it may ſeem a reaſonable concluſion, that the leaſt circular ſpace within which parallel rays of all kinds can be gathered by an object-glaſs compoſed of crown and flint-glaſs, ought to be one ſixth of one fifty-fifth part of its aperture. The difference in the focal lengths of the eye-glaſſes will then render the indiſtinctneſs nearly equal in the two kinds of object-glaſſes with equal magnifying powers, in all caſes where their apertures are equal, and their lengths as one to ſix.

There is, however, a circumſtance of the greateſt moment to be taken into account before this concluſion can be admitted, which is, that not merely the diameter of the circle of aberration is to be conſidered, but alſo the ſpiſſitude of the rays, both within that circle in general, and at different diſtances from its centre. The rarity of the light in the ſimple ſpectrum is ſuch, that the aberration hurts much leſs than might be expected. But in the ſecondary ſpectrum, as two orders of coloured light are united, the imperfect union of the rays by the compound object-glaſs, will hurt the diſtinctneſs much more, in proportion to the extreme divergency.

On this account it is to be expected, that the proportional lengths of the ſpectrums, when the experiment comes to be properly made, will turn out leſs than as one to ſix, notwithſtanding the degree in which the diſtinctneſs is hurt in the two kinds of teleſcopes, from the unequal refrangibility of light, may be nearly in that proportion.

The principal improvement of refracting teleſcopes, pointed out by the preceding experiments, conſiſts in an entire removal of this aberration from the unequal refrangibility of light. It appears from the performance of the ſmall teleſcope above mentioned, in which the ſecondary colour is not removed, that conſiderable advantages may alſo be expected from ſubſtituting a more perfect medium for flint-glaſs; from a more perfect correction of the aberration from the ſpherical figure; from preventing that loſs of light by reflection, which takes place when light enters into, or emerges from denſe mediums ſurrounded with air; and from diminiſhing thoſe errors which ariſe from faults in the workmanſhip.

THE diſadvantages under which reflecting teleſcopes labour, ariſe from their requiring larger apertures to tranſmit the ſame quantity of light; from being found to be more affected by imperfections of the atmoſphere than refracting teleſcopes, and being liable to tarniſh; but principally from imperfections in the workmanſhip of the object ſpeculum hurting their performance much more than equal imperfections in the object-glaſs hurt refractors.

THE deviation of a ray from its intended courſe, occaſioned by an imperfection in the figure of a reflecting ſpeculum, is to its deviation, ariſing from an equal imperfection in a lens, as four to one, when the ray paſſes from glaſs into air, and in the proportion of ſix to one, when it paſſes from air into glaſs. At a medium, therefore, it may be ſtated as five to one. It follows from hence, that ſuppoſing all other cauſes of imperfection removed but this of workmanſhip, and that the metal of ſpeculums were capable of as good a poliſh as glaſs, and of reflecting as much light as glaſs tranſmits, ſtill the perfection of the images of objects formed by refraction would greatly exceed thoſe by reflection.

SUCH is the caſe in the refractions which take place in the confine of glaſs and air. But in the refractions made in the confine of glaſs, and mediums of greater denſity than air, the difference is ſtill much greater.

THE proportion of the ſine of the angle of incidence to the ſine of the angle of refraction of a ray in paſſing out of one medium into another medium, is compoſed of the proportion of the ſine of the angle of incidence to the ſine of the angle of refraction out of the firſt medium into any third medium, and of the proportion of the ſine of the angle of incidence to the ſine of the angle of refraction, out of that third medium into the ſecond medium.

THUS,

Thus, if the ſine of the angle of incidence of any ray, in paſſing out of glaſs into air, be to the ſine of its angle of refraction as twenty to thirty-one, and the ſine of the angle of incidence of the ſame ray, in paſſing from air into oil of turpentine, be to the ſine of its angle of refraction as twenty-five to ſeventeen, the proportion of the ſine of the angle of incidence of that ray, to the ſine of its angle of refraction, in paſſing out of glaſs into oil of turpentine, will be as five hundred to five hundred and twenty-ſeven.

Hence the point to which light is converged by the refraction of a ſpherical ſegment of glaſs, ſurrounded with oil of turpentine, will be found to be above eighteen ſemi-diameters of the ſphere from the apex of the lens, when light paſſes from oil of turpentine into glaſs, and ſeventeen ſemi-diameters of the ſphere diſtant from the ſpherical ſegment, when light paſſes from glaſs into oil of turpentine; whereas in glaſs ſurrounded by air, the focal diſtance in theſe two caſes is only two ſemi-diameters, and three ſemi-diameters; and when light is converged to a point by a concave reflecting ſpeculum, the focal diſtance is only half a ſemi-diameter of the ſphere to which the ſpeculum is ground concave. Now, in all theſe caſes, the errors of the rays ariſing from imperfections in the workmanſhip of object-glaſſes, or object-ſpeculums, are as the focal diſtances to the radii of convexity; ſo that what Sir Isaac Newton mentions, of his having nearly deſpaired of reflecting teleſcopes from this conſideration, need not be wondered at.

The great pains, however, which he took with his own hands, and the ingenious methods which he ſuggeſted, and which have been ſo ably proſecuted ſince his time, have gone farther than could be expected towards obviating this fundamental fault of reflectors. Whatever can be performed by reflection, may be expected from the long experience and indefatigable exertions of Dr Herschel, aided by the countenance

nance and liberal ſupport of the Royal Founder of our Society, the general Patron of Science.

I APPREHEND there is a cauſe which will render ſhort teleſcopes always more diſtinct than long ones, where all other circumſtances are, as nearly as poſſible, alike; and that it has operated in favour of reflecting teleſcopes. It is well known that groſs bodies act on light at a diſtance. Some phenomena I have obſerved, appear to me to put it beyond doubt, that light alſo acts upon light, in ſuch a way as to propagate this action of groſs bodies much farther than is imagined. But I muſt delay entering farther on this ſubject; and ſhall only obſerve, that it was principally with an eye to this circumſtance, that I endeavoured in my attempts to execute object-glaſſes on the above principles, to ſtrain the increaſe of aperture to the utmoſt.

IT will be underſtood, that when the aberrations from the difference of refrangibility of light, and from the ſpherical figures of lenſes are removed, there remains no farther limit to ſhortening teleſcopes, excepting from the requiſite depth of the ſpheres and thickneſs of the glaſſes.

I FIND that in ſmall object-glaſſes of about nine inches focal length, the aperture may be increaſed as far as three inches, and hardly beyond this, on account of the quick increaſe of depth of the ſpherical ſurfaces, and thickneſs of the glaſs. From the difficulty found in procuring good glaſs of ſufficient thickneſs, it may perhaps be better to make the aperture for common purpoſes leſs than this. I ſhall therefore ſtate it at two inches. Hence the lengths neceſſary for increaſed apertures may readily be found, as the increaſe of length is in the ſame ratio as the increaſe of aperture, a double aperture requiring a double length, and ſo forth. Theſe lengths and apertures may be compared with the lengths and apertures neceſſary in ſingle lenſes, and in different kinds of reflectors, by the common tables.

It appears from the preceding experiments, that in compound object-glaſſes of crown and flint-glaſs, there is only a partial correction of the aberration from unequal refrangibility, and therefore in them, and others of that kind, the apertures and magnifying powers muſt only be increaſed in a ſubduplicate ratio of the increaſe of length, as in ſingle lenſes.

I will not pretend to ſtate with abſolute certainty the preciſe aperture which an achromatic teleſcope of a given length ought to have. This muſt be determined by experience. If two inches be taken for the greateſt aperture which ought to be given to a teleſcope of this kind two and thirty inches long, then three inches will be too much for one of forty-two inches, as hath been already obſerved. But whichſoever of theſe lengths and apertures be taken as the ſtandard, it is certain, that if we would avoid a greater degree of that indiſtinctneſs which is occaſioned by the aberration from difference of refrangibility, the aperture and magnifying power muſt not be increaſed in a greater proportion than the ſquare root of the increaſed length. Beſides, therefore, that this imperfect correction renders ſuch teleſcopes incapable of bearing high magnifying powers for thoſe of moderate lengths, large inſtruments, if they were to be attempted, would ſtill be unmanageable, on account of their immoderate lengths. The focal length of an object-glaſs of this kind, four feet in diameter, would require to be upwards of fifteen hundred feet, in order to enable it to bear the magnifying power adapted to that aperture, with the ſame diſtinctneſs that is found in an object-glaſs two inches in diameter, and thirty-two inches in focal length. But when the aberration from difference of refrangibility is totally removed, the focal length of an object-glaſs four feet in diameter, need not exceed twenty feet.

Having mentioned to ſome friends the imperfect correction of the aberration from difference of refrangibility, which is obtained by the common combination of two mediums which differ in diſperſive power, I was informed that ſomething of the ſame kind had been obſerved by ſome foreign philoſophers, and in particular by the celebrated M. Clairaut and M. Boscovich.

The obſervation of the former appears in a Memoir of the French Academy of Sciences, of ſo old a date as the year 1757. As the paſſage relating to this ſubject is ſhort, and does great credit to the author, as an accurate obſerver of the reſults of experiments, I ſhall beg permiſſion to tranſcribe it. "Il y a encore un fait important que nos experiences nous ont appris, c'eſt que les corrections des iris faites par les priſmes combinés, ne ſont jamais auſſi parfaites qu'on le croiroit d'après les termes de M. Dollond. Dans le cas du priſme de verre placé dans l'eau; par example, après avoir fait varier les plaques qui determinent l'angle du priſme d'eau, juſqu'au point où les objects vûs à travers les deux priſmes, ne paroiſſent point décolorés, du moins aux vûes ordinaires, on trouve en plaçant ces priſmes dans la chambre noire, qu'il reſte toûjours quelque petit limbe de couleur vers les bordes de l'image du ſoleil, ce qui vient ſans doute de ce que les parties du ſpectre que chaque matiere réfringente donne, ne ſont pas exactement proportionelles aux longueurs totales de ces ſpectres. Mais ces inégalités qui deminuent à meſure que les angles des priſmes ſont plus petits, doivent étre comme inſenſibles dans le cas des lentilles adoſſées, vû la petiteſſe des angles de refringence qui ont lieu alors." I ſhall only remark on this paſſage, that M. Clairaut would have obſerved the uncorrected colour better, if he had made uſe of a much ſmaller pencil of light than he appears to have done, and would not have concluded ſo haſtily that this uncorrected aberration was of little conſequence to the performance of teleſcopes, if he had recollected that the ſmallneſs of the angles of the lenſes is greatly overbalanced by the magnifying power of the eye-glaſs.

Mr Boscovich formed an hypotheſis concerning a perfect correction of colour, by a combination of mediums, which appears to have greatly miſled him. As a combination of two mediums is neceſſary to unite two of the unequally refrangible rays, he imagines three mediums neceſſary to unite three, four to unite four, and, in ſhort, that to effect a perfect union of the rays of the ſpectrum, as many mediums are required as there are unequally refrangible rays compoſing it, that is to ſay, an indefinite number. He ſuppoſes, however, that an union of three of the rays only, by means of three mediums, would greatly improve teleſcopes. This author ſeems to have founded his hypotheſis on the ſame kind of looſe analogical reaſoning, which had before led the celebrated Euler into a ſimilar miſtake.

The eye is compoſed of three humours and ſeveral coats; and M. Boscovich takes it for granted, that a more perfect union of the rays than what takes place in a combination of crown and flint-glaſs, is effected by their means. But this is a ſuppoſition very remote from the truth indeed. So far is this ſecondary colour from being corrected in the human eye, that in the conſtruction of this admirable organ, it hath been deemed unneceſſary to introduce any contrivance for the correction of the Newtonian aberration. *Natura nihil agit fruſtra.* The perfection of the Contriver equally appears from a manifeſtation of his power, and of his œconomical exertion of that power. On account of the ſhortneſs of the focal diſtance of the humours of the eye, in proportion to the aperture of the pupil, the aberration from the ſpherical figure would be ~~erro[illegible]~~ enormous; and we find it obviated by the very elaborate artifice of rendering the chryſtalline humour more denſe towards the centre. The aberration from difference of refrangibility might have been removed by imparting a proper degree of diſperſive power to the vitreous humour. But this, being unneceſſary for the common purpoſes of life, is withheld.

Dr **Maskelyne** has taken the pains to compute the quantity of this aberration in the eye, and is of opinion that it is not incompatible with diſtinct viſion *. But as it has been juſt aſſerted as a matter of fact, that the aberration from difference of refrangibility is not corrected in the human eye, it will be expected that the proofs on which this aſſertion is founded, ſhould be explained. Theſe are ſo ample as to leave no cauſe of uncertainty; nor are the neceſſary experiments attended with much trouble. For it happens that the humours are better placed for the purpoſe in the natural eye, than art could diſpoſe them elſewhere.

When I take the penknife which now lies before me, and hold it between me and the ſky, at the diſtance to which the eye is conformed for diſtinct viſion, the blade appears diſtinct, and well defined. If the eye be now accommodated to a more diſtant object, the blade of the knife begins to be ſurrounded with a penumbra; and if this penumbra be carefully attended to, it appears to be coloured, and the colour next to the knife is red inclining to orange, which is the colour of the leaſt refrangible rays.

If the eye be again accommodated to the diſtance neceſſary for ſeeing the knife diſtinctly, the bars of the window, which is at a greater diſtance than the knife, are ſurrounded with a penumbra, and the colour of this penumbra is blue, which is the prevailing colour of the moſt refrangible rays. The ſame appearances will be obſerved in all caſes where the confine of a dark and luminous object is carefully examined, and will be ſo much the more conſpicuous by how much the contraſt of light and darkneſs is ſtronger. It requires, however, a capacity of viewing with attention an object to which the eye is not conformed, which muſt be acquired by habit. The following eaſy experiment may be tried by any one. Shutting one eye, obſerve with the other the four well defined black pa-

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* Philoſophical Tranſactions of London, Vol. lxxix. p. 256.

rallel lines which denote four o'clock in the enamelled dial-plate of a watch, and make the watch approach the eye very ſlowly. So long as the eye can conform itſelf to the diſtance, the black lines will appear diſtinct and of their proper colours. But when the watch, continuing to approach, is brought too near for the eye, by any effort, to ſee the lines diſtinctly, the coloured fringes will begin to make their appearance, and the ſpreading of the leſs refrangible rays into the black ſtrokes, and the more refrangible rays into the white intervals, will make them appear to change their colours from black and white to orange and blue.

If any doubt ſhould remain concerning the priſmatic colour produced by the refraction of the humours of the eye, let the obſerver look at a bar of the window, where it is oppoſed to the ſky, and holding his hand parallel with the bar, bring it ſlowly over his eye, he will obſerve, juſt before the bar diſappears, one ſide of it edged with red inclining to orange, and the other with blue, and theſe colours in as great quantity as would be produced by a priſm of a pretty conſiderable refracting angle. The application of theſe obſervations to what was before ſaid of the fringes of colour produced by ſimple and compound lenſes, is obvious. If the aberration from difference of refrangibility were perfectly corrected, no colour whatever would appear, either in the penumbras, or on covering part of the pupil. Had this been effected, it is probable that the vitreous humour would be found ſufficiently diſperſive to correct the colour produced by the aqueous and cryſtalline humours, and that the ratio in which it ſeparated the rays which form the coloured ſpectrum, would be the ſame as in them. Such a colourleſs refraction might then be produced as has been found to ariſe from a combination of crown-glaſs with a fluid medium, containing a due proportion of metallic particles and particles of marine acid.

If the coloured penumbras, inſtead of being red when the eye is conformed to a greater diſtance than that of the object obſerved, and blue when conformed to a leſs diſtance, had been purple in the former caſe, and green in the latter, it would be reaſonable to conclude, that the vitreous humour was a diſperſive medium of the ſame kind with eſſential oils, and ſuch as owe this property to metalline particles with which they are impregnated.

But if the purple fringe had appeared round the object, when the eye is conformed to too ſmall a diſtance for ſeeing it diſtinctly, and with a green fringe under the contrary circumſtances, this would indicate a diſperſive power in the vitreous humour, ſimilar to that of the muriatic acid.

In ſome animals, and particularly in birds of prey, the images of objects on the retina are required to be more perfect than in the human eye. It would be an object of ſome moment in comparative phyſiology, to determine whether there be any partial or total correction of aberration from the difference of refrangibility in the eyes of theſe animals, which, if found neceſſary, will without doubt be the caſe. In ſome experiments which I once attempted with the vitreous humour, I found irregularities ariſe in the refraction, from giving it a figure different from its natural one. Poſſibly ſuch difficulties might be obviated by diluting the humours with ſome mild fluid of known optical properties.

The aberration from unequal refrangibility not being corrected in the eye, is one cauſe why viſion through a good teleſcope is more perfect, independent of magnifying power, than naked viſion when moſt perfect; a fact which muſt appear ſo extraordinary, that it can ſcarcely be expected to be credited, except by thoſe who have convinced themſelves of it by experience.

In order to explain this, it muſt be obſerved, that the ultimate effect required to be produced by a teleſcope or microſcope, is not a perfect union of the rays at the focus of the object-glaſs, but at the retina. This is to be effected by ſo diſpoſing the rays at their emergence from the eye-glaſs, that the humours of the eye ſhall accurately converge each of the pencils to one point of the retina. If we conceive a point of the retina to become a radiant point whence the rays iſſue, the rays of different colours, at their emergence from the cornea, will be inclined to each other in a certain degree, on account of their unequal refrangibility, and will continue to diverge, till they arrive, we ſhall ſuppoſe, at the eye-glaſs. Now, this is exactly the ſtate in which rays emerging from the eye-glaſs, and tending towards the eye, ought to be, in order to inſure their perfect union at that point of the retina from which the above mentioned rays were ſuppoſed to radiate.

Another cauſe which operates in favour of teleſcopic viſion, is the ſmallneſs of the pencil where it enters the eye. When the diameter of the pencil is equal to that of the pupil, the rays, in paſſing the edge of the iris, are inflected, that is to ſay, they are made to deviate from their rectilineal courſe, ſome of them being bent towards the iris, and others from it, and thus throw a ſcattered light round the image on the retina. The radiation of the bright fixed ſtars proceeds partly from this cauſe. This ſource of indiſtinctneſs is totally removed in a teleſcope, where the diameter of the pencil, at its entrance into the eye, is ſo much leſs than the pupil, that none of the rays paſs near enough the iris to ſuffer any inflection. The ſize of the pencil muſt not, however, be diminiſhed too far; for if this is done beyond a certain degree, the diſtinctneſs will be quite deſtroyed, as was firſt obſerved by Hugenius.

I shall now recapitulate, and preſent in one view, the contents and ſcope of this diſcourſe.

The unequal refrangibility of light, as diſcovered and fully explained by Sir Isaac Newton, ſo far ſtands its ground uncontroverted, that when the refraction is made in the confine of any medium whatever, and a vacuum, the rays of different colours are unequally refracted, the red-making rays being the leaſt refrangible, and the violet-making rays the moſt refrangible.

THE diſcovery of what has been called a different diſperſive power in different refractive mediums, proves thoſe theorems of Sir ISAAC NEWTON not to be univerſal, in which he concludes that the difference of refraction of the moſt and leaſt refrangible rays, is always in a given proportion to the refraction of the mean refrangible ray. There can be no doubt that this poſition is true with reſpect to the mediums on which he made his experiments; but there are many exceptions to it.

FOR the experiments of Mr DOLLOND prove, that the difference of refraction between the red and violet rays, in proportion to the refraction of the whole pencil, is greater in ſome kinds of glaſs than in water, and greater in flint-glaſs than in crown-glaſs.

THE firſt ſet of experiments above recited, prove, that the quality of diſperſing the rays in a greater degree than crown-glaſs, is not confined to a few mediums, but is poſſeſſed by a great variety of fluids, and by ſome of theſe in a moſt extraordinary degree. Solutions of metals, eſſential oils, and mineral acids, with the exception of the vitriolic, are moſt remarkable in this reſpect.

SOME conſequences of the combinations of mediums of different diſperſive powers, which have not been ſufficiently attended to, are then explained. Although the greater refrangibility of the violet rays than of the red rays, when light paſſes from any medium whatever into a vacuum, may be conſidered as a law of nature; yet in the paſſage of light from one medium into another, it depends entirely on the qualities of the mediums, which of theſe rays ſhall be the moſt refrangible, or whether there ſhall be any difference in their refrangibility.

The application of the demonſtrations of Hugenius to the correction of the aberration from the ſpherical figures of lenſes, whether ſolid or fluid, is then taken notice of, as being the next ſtep towards perfecting the theory of teleſcopes.

Next it appears from trials made with object-glaſſes of very large apertures, in which both aberrations are corrected as far as the principles will admit, that the correction of colour which is obtained by the common combination of two mediums which differ in diſperſive power, is not complete. The homogeneal green rays emerge moſt refracted, next to theſe the united blue and yellow, then the indigo and orange united, and laſtly the united violet and red, which are leaſt refracted.

If this production of colour were conſtant, and the length of the ſecondary ſpectrum were the ſame in all combinations of mediums when the whole refraction of the pencil is equal, the perfect correction of the aberration from difference of refrangibility would be impoſſible, and would remain an inſurmountable obſtacle to the improvement of dioptrical inſtruments.

The object of the next experiments is, therefore, to ſearch, whether nature affords mediums which differ in the degree in which they diſperſe the rays compoſing the priſmatic ſpectrum, and at the ſame time ſeparate the ſeveral orders of rays in the ſame proportion. For if ſuch could be found, the above mentioned ſecondary ſpectrum would vaniſh, and the aberration from difference of refrangibility might be removed. The reſult of this inveſtigation was unſucceſsful with reſpect to its principal object. In every combination that was tried, the ſame kind of uncorrected colour was obſerved, and it was thence concluded, that there was no direct method of removing the aberration.

But it appeared in the courſe of the experiments, that the breadth of the ſecondary ſpectrum was leſs in ſome combinations than in others, and thence an indirect way opened, leading to the correction ſought after; namely, by forming a compound concave lens of the materials which produce moſt colour, and combining it with a compound convex lens formed of the materials which produce leaſt colour; and it was obſerved in what manner this might be effected by means of three mediums, though apparently four are required.

In ſearching for mediums beſt adapted for the above purpoſe, a very ſingular and important quality was detected in the muriatic acid. In all the diſperſive mediums hitherto examined, the green rays, which are the mean refrangible in crown-glaſs, were found among the leſs refrangible, and thence occaſion the uncorrected colour which has been deſcribed. In the muriatic acid, on the contrary, theſe ſame rays make a part of the more refrangible; and in conſequence of this, the order of the colours in the ſecondary ſpectrum, formed by a combination of crown-glaſs with this fluid, is inverted, the homogeneal green being now the leaſt refrangible, and the united red and violet the moſt refrangible.

This remarkable quality found in the marine acid led to complete ſucceſs in removing the great defect of optical inſtruments, that diſſipation or aberration of the rays, ariſing from their unequal refrangibility, which has rendered it impoſſible hitherto to converge all of them to one point, either by ſingle or oppoſite refractions. A fluid in which the particles of marine acid and metalline particles hold a due proportion, at the ſame time that it ſeparates the extreme rays of the ſpectrum much more than crown-glaſs, refracts all the orders of rays exactly in the ſame proportion as the glaſs does; and hence rays of all colours, made to diverge by the refraction of the glaſs, may either be rendered parallel by a ſubſequent refraction made in the confine of the glaſs and this fluid, or by weakening the refractive denſity of the fluid, the refraction which takes place in the confine of it and glaſs, may be rendered as regular as reflection, while the errors ariſing from unavoidable imperfections of workmanſhip, are far leſs hurtful than in reflection, and the quantity of light tranſmitted by equal apertures of the teleſcopes much greater.

Such are the advantages which the theory preſents. In reducing this theory to practice, difficulties muſt be expected in the firſt attempts. Many of theſe it was neceſſary to ſurmount before the experiments could be completed. For the delicacy of the obſervations is ſuch, as to require a conſiderable degree of perfection in the execution of the object-glaſſes, in order to admit of the phenomena being rendered more apparent by means of high magnifying powers. Great pains ſeem to have been taken by mathematicians to little purpoſe in calculating the radii of the ſpheres requiſite for achromatic teleſcopes, from their not conſidering that the object-glaſs itſelf is a much nicer teſt of the optical properties of refracting mediums than the groſs experiments made by priſms, and that the reſults of their demonſtrations cannot exceed the accuracy of the data, however much they may fall ſhort of it.

I shall conclude this paper, which has now greatly exceeded its intended bounds, by enumerating the ſeveral caſes of unequal refrangibility of light, that their varieties may at once be clearly apprehended.

In the refraction which takes place in the confine of every known medium and a vacuum, rays of different colours are unequally refrangible, and the red-making rays are leaſt refrangible, and the violet-making rays are moſt refrangible.

This difference of refrangibility of the red and violet rays is not the ſame in all mediums. Thoſe mediums in which the difference is greateſt, and which, by conſequence, ſeparate or diſperſe the rays of different colours moſt, have been diſtinguiſhed by the term *diſperſive*, and thoſe mediums which ſeparate the rays leaſt have been called *indiſperſive*. Diſperſive mediums differ from indiſperſive, and ſtill more from each other, in another very eſſential circumſtance.

It appears from the experiments which have been made on indiſperſive mediums, that the mean refrangible light is always the ſame, and of a green colour.

Now, in by far the largeſt claſs of diſperſive mediums, including flint-glaſs, metallic ſolutions, eſſential oils, the green light is not the mean refrangible order, but forms one of the leſs refrangible orders of light, being found in the priſmatic ſpectrum nearer to the deep red than the extreme violet.

In another claſs of diſperſive mediums, which includes the muriatic and nitrous acids, this ſame green light becomes one of the more refrangible orders, being now found nearer to the extreme violet than the deep red.

These are the varieties in the refrangibility of light, when the refraction takes place in the confine of a vacuum; and the phenomena will ſcarce differ ſenſibly in refractions made in the confine of denſe mediums and air.

But when light paſſes from one denſe medium into another, the caſes of unequal refrangibility are more complicated.

In refractions made in the confine of mediums which differ only in ſtrength, not in quality, as in the confine of water and crown-glaſs, or in the confine of the different kinds of diſperſive fluids more or leſs diluted, the difference of refrangibility will be the ſame as above ſtated in the confine of denſe mediums and air, only the whole refraction will be leſs.

In the confine of an indiſperſive medium, and a rarer medium belonging to either claſs of the diſperſive, the red and violet rays may be rendered equally refrangible. If the diſperſive power of the rare medium be then increaſed, the violet rays will become the leaſt refrangible, and the red rays the moſt refrangible. If the mean refractive denſity of the two mediums be rendered equal, the red and violet rays will be refracted in oppoſite directions, the one towards, the other from the perpendicular.

Thus it happens to the red and violet rays, whichſoever claſs of diſperſive mediums be employed. But the refrangibility of the intermediate orders of rays, and eſpecially of the green rays, will be different when the claſs of diſperſive mediums is changed.

Thus in the firſt caſe, where the red and violet rays are rendered equally refrangible, the green rays will emerge moſt refrangible, if the firſt claſs of diſperſive mediums is uſed, and leaſt refrangible if the ſecond claſs is uſed. And in the other two caſes, where the violet become leaſt refrangible, and the red moſt refrangible, and where theſe two kinds of rays are refracted in oppoſite directions, the green rays will join the red, if the firſt claſs of diſperſive mediums be employed, and will arrange themſelves with the violet, if the ſecond claſs be made uſe of.

Only one caſe more of unequal refrangibility remains to be ſtated; and that is, when light is refracted in the confine of mediums belonging to the two different claſſes of diſperſive fluids. In its tranſition, for example, from an eſſential oil, or a metallic ſolution, into the muriatic acid, the refractive denſity of theſe fluids may be ſo adjuſted, that the red and violet rays ſhall ſuffer no refraction in paſſing from the one into the other, how oblique ſoever their incidence be. But the green rays will then ſuffer a conſiderable refraction, and this refraction will be from the perpendicular, when light paſſes from the muriatic acid into the eſſential oil, and towards the perpendicular, when it paſſes from the eſſential oil into the muriatic acid. The other orders of rays will ſuffer ſimilar refractions, which will be greateſt in thoſe adjoining the green, and will diminiſh as they approach the deep red on the one hand, and the extreme violet on the other, where the refraction ceaſes entirely.

The manner of the production of theſe effects, by the attraction of the ſeveral mediums, may be thus explained.

We ſhall ſuppoſe the attractive forces, which produce the refractions of the red, green and violet light, to be repreſented by the numbers eight, twelve and ſixteen, in glaſs; ſix, nine, fourteen, in the metallic ſolution; ſix, eleven, fourteen, in the muriatic acid; and ſix, ten, fourteen, in a mixture of theſe two fluids. The exceſs of attraction of glaſs for the red and violet light is equal to two, whichſoever of the three fluids be employed. The refraction of theſe two orders of rays will therefore be the ſame in all the three caſes. But the exceſs of attraction for the green light is equal to three, when the metallic ſolution is uſed, and therefore the green light will be more refracted than the red and violet, in this caſe. When the muriatic acid is uſed, the exceſs of attraction of glaſs for the green light is only one, and therefore the green light will now be leſs refracted than the red and violet. We ſhall next ſuppoſe the metallic ſolution and the acid to adjoin each other. The attractions of both theſe mediums, for the red light being ſix, and for the violet light fourteen, theſe two orders of rays will ſuffer no refraction in the confine of the two fluids, the difference of their attractions being equal to nothing.

But the attractive force of the metallic ſolution for the green ray being only nine, and that of the muriatic acid for the ſame ray being eleven, the green light will be attracted towards the muriatic acid with the force two; and therefore the difference between the refraction of the green light and the unrefracted red and violet light which takes place in the confine of theſe fluids, will greatly exceed the difference of refraction of the green light, and equally refracted red and violet light, which is produced in the confine of glaſs and either of the fluids.

Lastly, in a mixture of the two kinds of fluids, the attraction for the red, green and violet rays, being ſix, ten and fourteen, and that of the glaſs, eight, twelve and ſixteen, the exceſs of the attraction of the glaſs for the green rays, is the ſame which it is for the red and violet rays. Theſe three orders of rays will therefore ſuffer an equal refraction, being each of them attracted towards the glaſs with the force two; and when this is the caſe, it appears from the obſervations, that the indefinite variety of rays of intermediate colours and ſhades of colours, which altogether compoſe ſolar light, will alſo be regularly bent from their rectilinear courſe, conſtituting what has been termed *aplanatic refraction*.

THESE caſes of attraction might be farther illuſtrated by means of diagrams. But after the explanation already given of the ſecond, third, fourth, fifth, ſixth, ſeventh and eighth figures, this would be unneceſſary. And it need ſcarcely here be obſerved, that the above rough ſtatements in round numbers, are intended to give a clear idea of the nature of the various caſes of unequal refrangibility, and not to aſcertain its quantity in any particular caſe. A full inveſtigation of the ſubject, and an account of ſome digreſſions leſs immediately connected with the principal object which occurred in the courſe of the enquiry, could not be brought within the compaſs of the preſent communication.

Fig. 1.

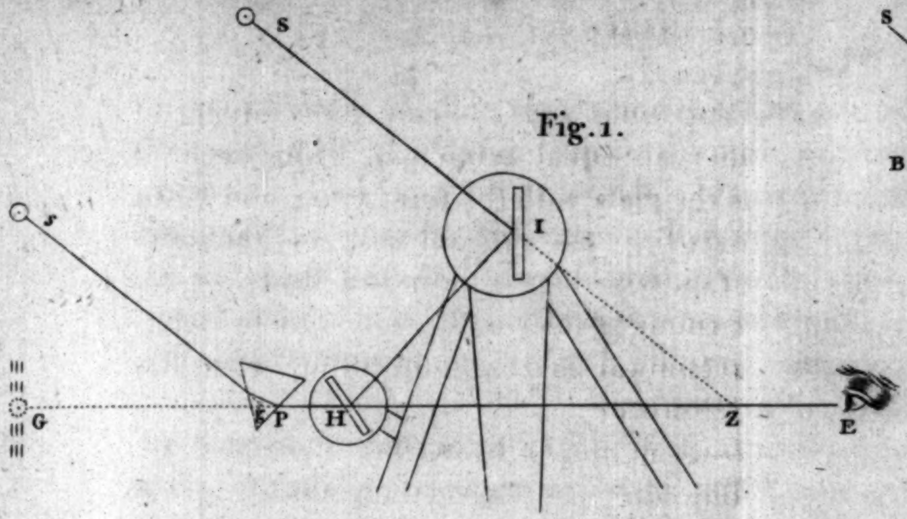
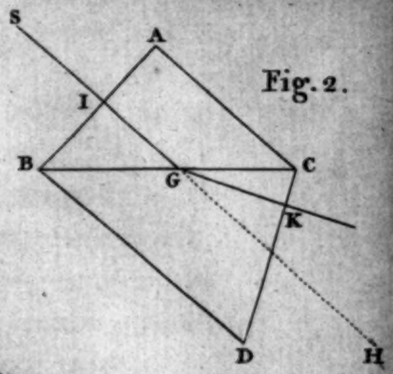


Fig. 2.



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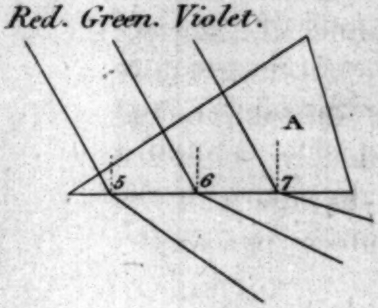

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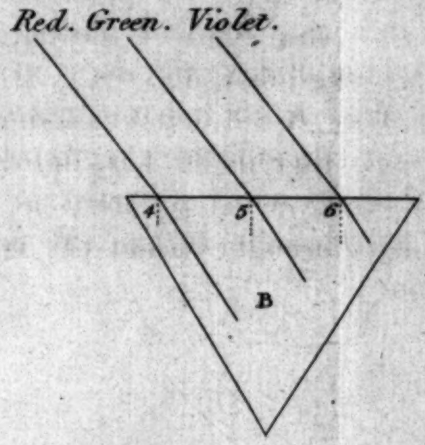

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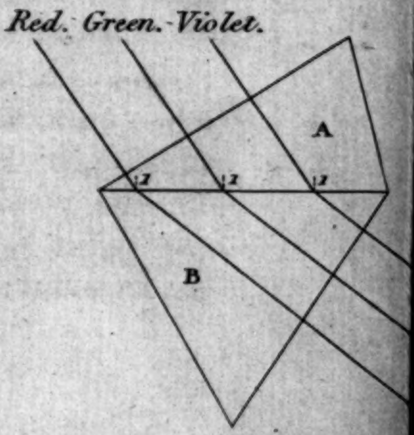

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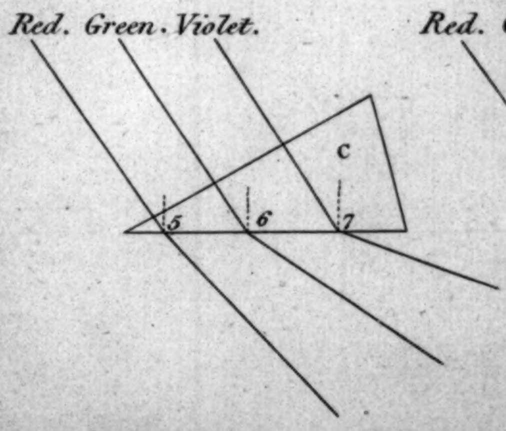

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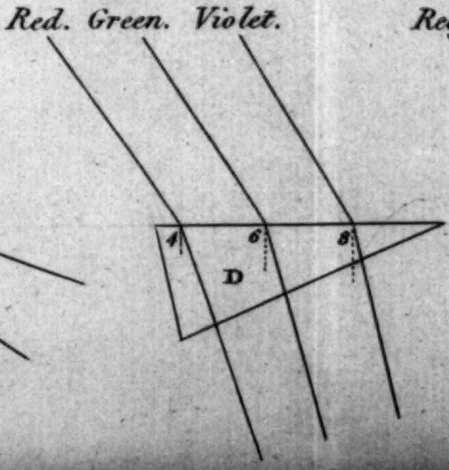

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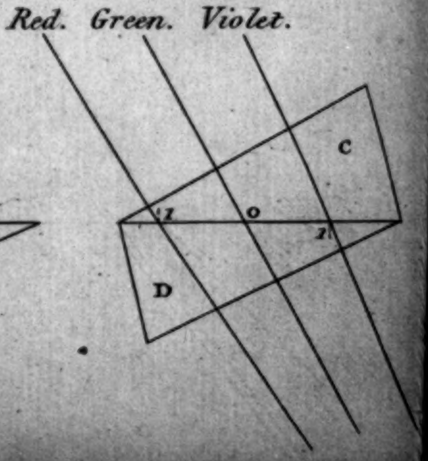

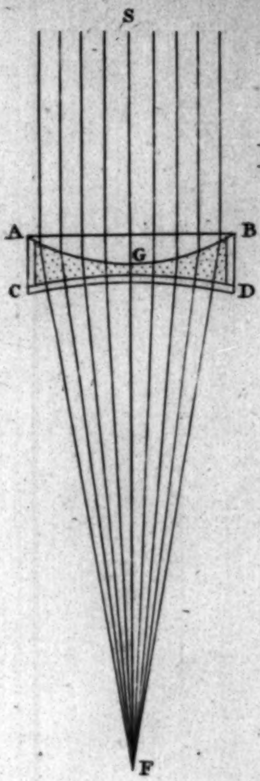
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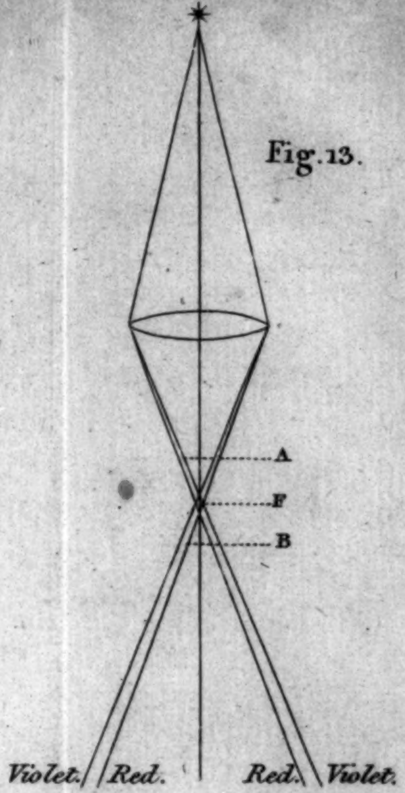
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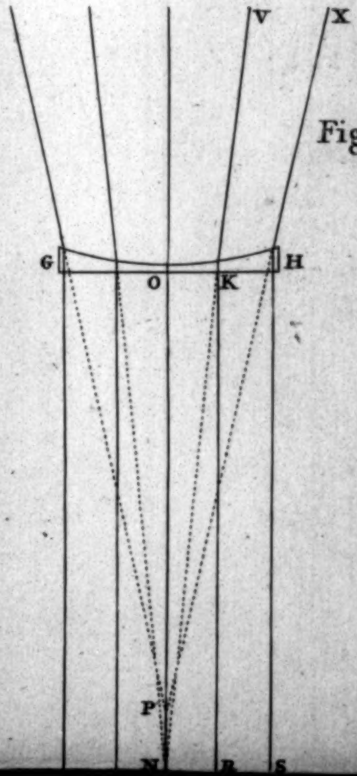
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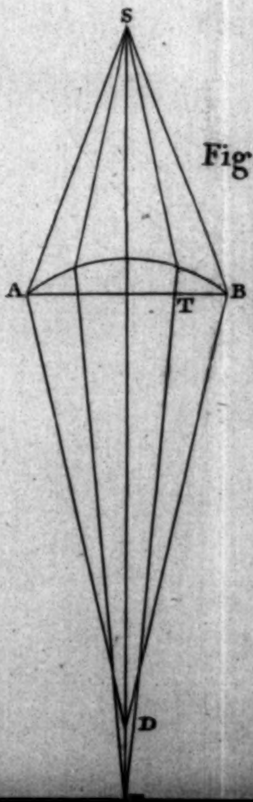
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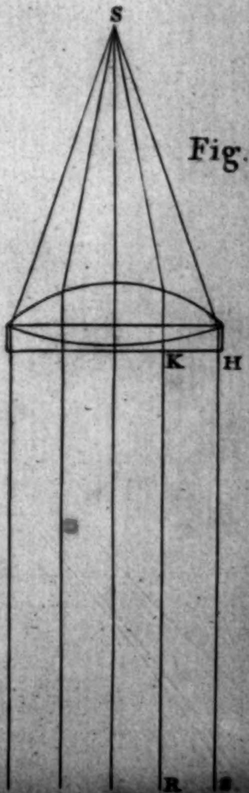
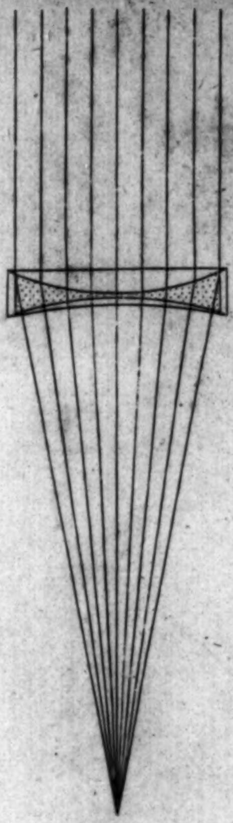


Fig. 12.

Fig. 20.



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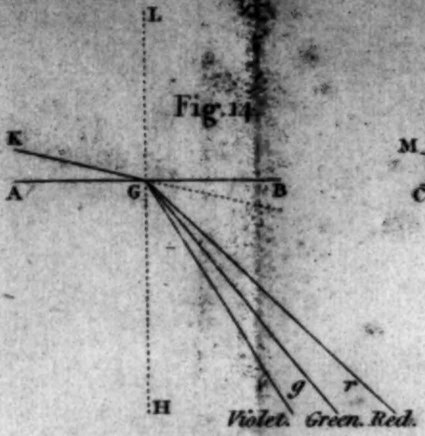

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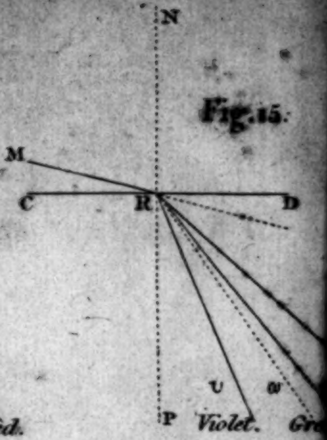

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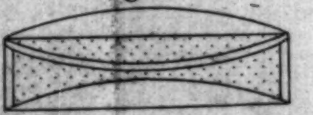

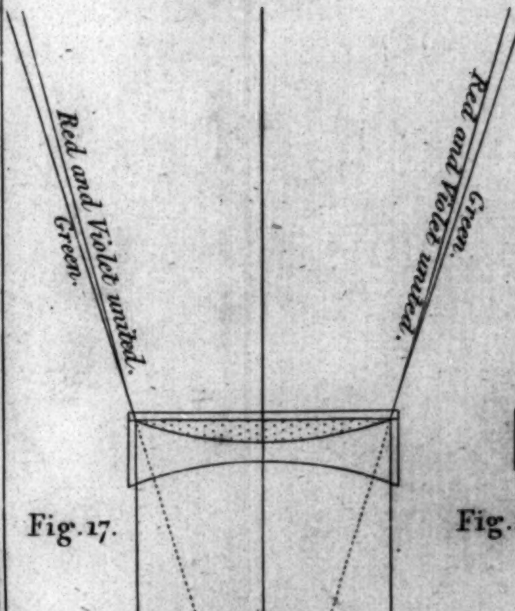

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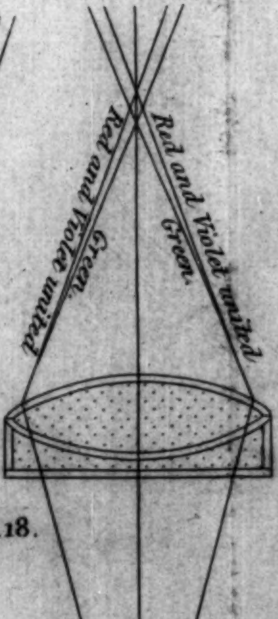

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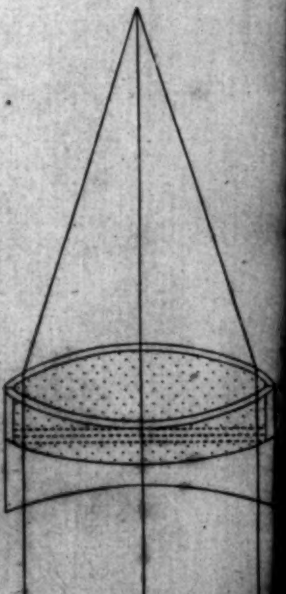

Fig. 19.